Hogarth P. I.

PhD Thesis

June 2021

UK Mean Sea Level Change from Analysis of Tide Gauge Records

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy

by

Peter Ian Hogarth

June 2021

Faculty of Science and Engineering

School of Environmental Sciences

Department of Earth, Ocean and Ecological Sciences

Declaration of Authorship

I, Peter Ian Hogarth, declare that this thesis entitled *UK Mean Sea Level Change from Analysis of Tide Gauge Records* and all of the work presented in it are my own and have been generated by me as the result of my own original research done wholly during the course of a research degree at the University of Liverpool.

No part of this thesis has been submitted for a degree or any other qualification at this University or any other institution.

The published work of others has in all cases been clearly attributed and where I have quoted from the work of others, the source in all cases is given.

I have acknowledged all main sources of assistance

Where the thesis is based on work done by myself jointly with others, I have stated what my contribution was and what others contributed.

Parts of this thesis have been published as:

Hogarth, P., Hughes, C. W., Williams, S. D. P., & Wilson, C. (2020). Improved and extended tide gauge records for the British Isles leading to more consistent estimates of sea level rise and acceleration since 1958. *Progress in Oceanography* **184**, 102333. https://doi.org/10.1016/j.pocean.2020.102333.

Hogarth, P., D. T. Pugh, C. W. Hughes and S. D. P. Williams, 2021: Changes in mean sea level around Great Britain over the past 200 years. *Progress in Oceanography* **192**, 102521, https://doi.org/10.1016/j.pocean.2021.102521.

UK Mean Sea Level Change from Analysis of Tide Gauge Records

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Peter Ian Hogarth[1]. June 2021

p.hogarth@liverpool.ac.uk pehoga@noc.ac.uk peter.hogarth@yahoo.com

Supervisors: Chris Hughes[1,2], Simon Williams[2]

[1]Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool L69 3BX, UK.

[2]National Oceanographic Centre, 6 Brownlow Street, Liverpool L3 5DA, UK.

Abstract

This thesis is mainly concerned with changes in mean sea level as measured at coastal tide gauge sites around the coast of Great Britain, and addresses the question of whether a secular change in rate of rise of sea level can be discerned over the measurement period. This is an important question for the coastal and low-lying areas of not only the UK, but globally, with the IPCC estimating that 11% of the worlds population currently live in low elevation coastal zones, with sea level rise projected to impact available land area, coastal infrastructure, ecosystems and the viability of some island nations.

The two main thrusts of this present work are concerned with

1) Extending the temporal extent of currently available tide gauge records using data archaeology, ideally to the point where long term climate related trends emerge. This is important as currently many of the records are only a few decades long, and analysis of trends can give inconsistent results in relation to ongoing climate change. The small number of records which stretch back into the 19th Century do appear to show a long term increase in rate of sea level rise.

2) investigating optimal methods of identifying and accounting for any non-climate related variability in the records, again allowing any underlying trends to be more easily discerned, and importantly, shortening the period over which a climate related signal might be detected.

The results are conclusive. Long term sea level rise and acceleration are confirmed around the entire UK coastline. For sites where recent decadal scale sea level falls have been reported, these are shown to be due to a combination of datum control errors and insufficient record length. Datum shifts due primarily to instrumentation changes are shown to be a significant error source in many of the UK tide gauge records. Many of these shifts have not been differentiated from assumed inter-site variability due to other causes until now. Accounting for these shifts with recorded calibration data and knowledge of physical changes at the tide gauge allows these errors to be systematically reduced, to the point that inter-site variability and differences in global isostatic adjustment adjusted sea level rise are much smaller and records appear visually similar. A further result is that the similarity of tide gauge records from nearby locations along the same coastline coupled with low uncertainties in land based survey levelling over short distances allows the monthly or annual mean sea level time series from these locations to be combined into a single representative record with quantifiable uncertainties. Furthermore, the variation between records further apart is found to be mainly due to localised meteorological effects. We confirm that these effects are well described by a tide and surge model, and this allows this variability to be accounted for. This leaves a residual signal where the variability is shown to be largely common mode, and therefore likely to be a far field ocean related effect. The finding that remaining inter-site variability is small allows averaging of the tide gauge records to obtain a single representative UK sea level index. This methodology eases the extension of localised tide gauge records using even short sections of historical tide gauge data. A comprehensive data archaeology exercise was then carried out to recover as much of this data as possible, much of which was previously unpublished, and assimilate this data first into localised records and then into a single UK wide record stretching back over more than two centuries. Clear acceleration is evident, with upward changes in gradient around the end of the 19th and 20th Centuries. Over most of the 19th Century the rise in sea level appears to be close to zero, rising to an average of just over 2mm/yr during the 20th Century, and rising again to an average of 3.4 mm/yr in the 21st Century so far. The acceleration over the entire period is around 0.01 mm/yr^2 which is consistent with observed century scale sea level change when averaged globally. These data processing methods can be applied to other coastlines around the world where observations from tide gauges have been recorded.

Acknowledgements

This PhD study was supported by the Natural Environment Research Council (NERC) EAO Doctoral Training Partnership (DTP) and is fully funded by NERC whose support is very gratefully acknowledged. Grant ref. no. is NE/L002469/1, UKRI award ref. 1950000.

I would like to thank the University of Liverpool for offering me this research opportunity, which I had not anticipated even a year prior to my PhD interview, but which has been incredibly rewarding as well as incredibly hard work. I feel the outcome has been successful from several perspectives. I would also like to thank the various individuals, colleagues and acquired friends based at the National Oceanographic Centre (NOC), the PSMSL and BODC based at Liverpool who have made my research environment there enjoyable, good humoured, and so much more than just a place to work. My thanks go to DTP cohort colleagues from all year groups as well as my own and I'm grateful to Julie Samson for making each DTP event memorable. My supervisors Chris Hughes and Simon Williams have provided inspiration and empathy on top of their academic experience and world class technical expertise. Their on-line presence through the challenging periods of lockdown through 2020 and 2021 have kept me sane and relatively focussed. Phil Woodworth deserves special mention, as he is largely responsible for persuading me to finally publish my early work on sea level in 2014, and for putting the idea of a PhD into my head (partly in jest - at the time). David Pugh also provided a role model and inspiration for research involving data archaeology. A glance at the bibliography would show I also owe thanks to the many hundreds of people upon whose work research like this is built. It has been a team effort not just through my contemporaries. Last, but not least by some margin, I owe immense gratitude to my wife for her patience, support and encouragement through four years which have been immensely challenging, intense and rewarding, but which neither of us would ever want to repeat.

Contents

Abbreviations and definitions

CGPS. Continuous Global Positioning System refers to a GPS receiver system at a fixed land based location which is continuously measured and refined as positional data accumulates. This is particularly useful for monitoring variables like continental drift and vertical land motion. Over timescales of several years, it is possible to derive trends of geocentric movement in latitude, longitude, and elevation.

GIA. Glacial Isostatic Adjustment is the ongoing vertical movement of the earths crust in response to past changes in loading from glaciers and ice mass and associated changes to the earth's gravity field.

GPS. Global Positioning System, the original US Government owned satellite based radionavigation system designed so that a suitable receiver anywhere on earth could be precisely located relative to a constellation of orbiting satellites, and thus to a reference frame within which the satellite orbits are precisely defined.

GNSS. Global Navigation Satellite System, a generic term for satellite navigation systems (including GPS) that provide autonomous geo-spatial positioning with global coverage

HW. High Water is the highest point reached by the sea surface during a particular tidal cycle. Historical extreme HW values relating to coastal flooding are often well recorded.

IHO. The International Hydrographic Organisation is an intergovernmental body which aims to ensure all the world's oceans, seas, and navigable waters are surveyed and charted.

ITRF. International Terrestrial Reference Frame is an internationally accepted standard geocentric frame of reference points by which any location in the world at any time can be referenced. GNSS locations and elevations, satellite altimetry surface heights, and GIA models are all ultimately referenced to a version of the ITRF.

LW. Low Water is the lowest point reached by the sea surface during a particular tidal cycle.

MHW. Mean High Water, the average of HW readings over some period such as a month or year.

MLW. Mean Low Water, the average of LW readings over some period such as a month or year.

MSL. Mean Sea Level is defined as the average of frequently sampled (usually 15 minute or hourly) sea level measurements at a specific site over time, or the combination of several such records to give a regional or global mean (GMSL). Monthly means or annual means are usually used.

MTL. Mean Tide Level is usually the mean of average High Water (HW) and Low Water (LW) over time, but in some cases the mean of High Water Spring and Neap tides, and Low Water Spring and Neap tides is used. The differences are usually small. Historically the term half-tide is also used.

OHC. Ocean Heat Content. The change in the amount of thermal energy stored in the oceans compared to a reference period.

OS. Ordnance Survey. The National Land Mapping agency for Great Britain

PSMSL. Permanent Service for Mean Sea Level, the main repository for global quality controlled mean sea level data, which is publicly accessible

RSL. Relative Sea Level, the observed mean sea level measured relative to stable local land level, usually represented by fixed bench marks which are levelled to a national mapping datum. All PSMSL mean sea level records are RSL, and require adjustment for GIA to convert to SLR as defined below.

SLR. Sea Level Rise is defined here as an increase in mean sea level over time relative to a geocentric reference frame, measured in mm/yr. although it is also used generically to mean an increase in observed sea level.

SLA. Sea Level Acceleration is defined as an increase in the rate of SLR over time, here measured in mm/yr^2.

UKHO. United Kingdom Hydrographic Office, the UK government department responsible for charting the waters around the UK coastline and around the world. Part of the Admiralty.

Chapter 1: Introduction

1.1 Motivation and global context

Over the past few decades the study of sea level has become increasingly important as the main components of sea level rise (volume increase due to thermal expansion of the ocean and mass redistribution due to melting land based ice) are directly associated with ongoing anthropogenic climate change (Oppenheimer et al. 2019). Based on our current understanding of sea level rise (Frederikse et al. 2020a), the projected impacts to 2100 and beyond are significant (Mengel et al. 2018), with a committed sea level rise of 1m by 2300 even if all future emissions pledges are honoured (Nauels et al. 2019). However, current emissions trends are tracking the highest RCP8.5 scenario, (Schwalm et al. 2020) and observed sea level trends are currently in best agreement with projections for the higher CO2 emissions scenarios (Wang et al. 2021), implying a commitment of several metres of future sea level rise (Palmer et al. 2020). It is estimated that more than 600 million people currently live in low lying coastal zones, with this number predicted to increase despite population displacement from the most vulnerable coastal areas (Strauss et al. 2021). The rising sea level will not just affect coastal concentrations of urban populations and infrastructure, but will impact available land area along the entire coastline through increased flooding, erosion, salt intrusion and permanent inundation (Taherkhani et al. 2020), with associated changes to coastal ecosystems and tidal regimes.

There are large uncertainties in projected sea level trends, mainly due to the future contribution of the Antarctic ice sheet (Frederikse et al. 2020b, Slater et al. 2020). It is clearly vital that we continue investing in remote satellite based observation systems in order to have continuous records of global sea level and of the drivers of sea level going forward, but there are also uncertainties in the historical trends of sea level variation both globally and regionally due to sparseness of instrumental data as we look further back in time. It is important that we not only maintain our ability to measure sea level along the global coastline using tide gauges, but that we recover historical tide gauge observations in order to better understand longer term changes and regional variations. these shorter timescale variations are superimposed onto a longer term average sea level, which is currently rising due to climate change. This thesis is mainly concerned with this change in mean sea level (here monthly mean sea levels are used) as measured at coastal tide gauge sites around the coast of Great Britain, and addresses the question of whether a secular change in rate of rise of sea level can be discerned over the measurement period.

However, whilst the recorded changes in mean sea level around the UK may not be wholly representative of the wider global ocean, the processing steps are general, and the scope of application is intended to be global. Chapters 3 and 4 can therefore be viewed as UK based case studies as part of a larger global effort, and this is reflected in the large amount of global context given in this thesis.

In Europe in general, but particularly in the UK, the systematic recording of sea level observations was more widely promoted in the early 19th Century, as the prediction of tides and creation of accurate tide tables was a valuable aid in the efficient running of a global maritime trade network. The study of tides (as opposed to mean sea level) was part of a rising interest in observation based science and became an important subject in its own right. However, as will be clear, the fact that observations were originally recorded and are mentioned in historical documents does not mean that records were maintained or archived, and it is likely that many have not survived.

Tide gauge data is available from several regions around the world over much of the industrial period, but moving back before the second half of the 20th Century, the spatial distribution of tide gauge sites becomes sparse and more limited. This means that for many regions of the world we currently have a small number of sites with relatively short time series. These gaps in our knowledge can be reduced by attempting to extend time series where possible and addressing known causes of variability in available time series. This need has been identified previously (Caldwell 2012) and some important progress has already been made (see section 1.3)

The two main thrusts of this present work are concerned with:

1) **Extending the temporal extent of currently available tide gauge records** using data archaeology, ideally to the point where long term climate related trends emerge. This timescale depends on location as many regions are subject to higher natural variability (Hughes and Williams 2010) but is generally thought to be between 60 and 100 years for tide gauge data. Although many tide gauges were operating from the 19th Century onwards, records have been lost or remain as undigitized paper charts. Data archaeology is necessary to uncover and digitise any available data.

2) Investigating optimal methods of identifying and **accounting for any non-climate related variability** in the records, allowing any underlying trends to be more easily evaluated. This variability varies in timescale from daily (tidal) variations, easily accounted for here using

monthly means, to interannual or decadal scale fluctuations in water redistribution associated with ocean scale weather and current patterns represented by proxy factors such as the El Niño Southern Oscillation or Atlantic Meridional Oscillation. These recurrent fluctuations can bias derived trends even over timescales approaching a century (Hogarth 2014).

Although these two methods are explored for one region, the processing steps employed are general, and can thus be employed for other records globally. We also assess the possibility of constraining conclusions about global changes from long term regional studies. It is known that the spatial scale of coherent sea level variations increases as we look at longer timescales and lower frequencies (Douglas 1991), in some cases to many thousands of km. This suggests that at long enough (century scale and longer) timescales, globally common signals such as those due to secular climate change might be discerned and more easily separated from any natural variations and fluctuations which can operate over interannual and decadal timescales. It follows that if ocean climate signals can be robustly detected in sea level records from single regions, then this infers that they are present globally. Even small amounts of data from a handful of sites could help confirm this. The very few records that we have which start earlier than the late 19th Century are therefore valuable in a global as well as a regional context. Inevitably, these very old records are more likely to be available from sites in countries which already had a well developed marine infrastructure, the UK being a prime example.

1.3 Thesis chapter contents

Chapter 2 contains an introduction and literature review of available historical sea level data from around the world, and how this has been interpreted from work in the early 19th Century up to the present understanding.

Chapter 3 describes of some of the initial problems associated with processing sea level time series from tide gauges, and how this thesis addresses some of the more significant of these. The methods described apply not just to UK records.

Chapter 4 contains an investigation of MSL for the waters around the British Isles since 1958. This is a UK wide case study, which was published as a paper in “Progress in Oceanography” in 2020. We focus on improving the quality control of datum continuity.

Chapter 5 contains a longer term investigation of MSL around the British Isles, extending data back to the early 19th Century with largely unpublished data for a large number of sites. We again focus on the problem of vertical control to allow assimilation of short sections of data into longer records. This was published as a paper in “Progress in Oceanography” in 2021.

Chapter 6 discusses the results from both papers in the light of the most recent literature and the global sea level record.

Chapter 7 gives overall conclusions based on the analysis of UK sea level, briefly expands this within a more global context and suggests directions for further work.

The Appendix contains supplements (or links to on-line supplements) to the original published papers

This is followed by a comprehensive Bibliography

Chapter 2: Literature review

This chapter gives an overview of the progress of observation based sea level science over the past two centuries and more, and shows how the interpretation of sea level change and its causes altered as new data and knowledge was assimilated. Early work on sea level was derived from work on the tides, the daily or twice daily variations in sea level observed at the coast. In many places, this variation can reach amplitudes of several metres. When sea level change is discussed, it is usually based on continuous measurements averaged over a long enough period to minimise the daily and other periodic astronomical tidal variations. Here, most of the 20th Century data used consists of monthly mean sea level (MSL) based on hourly readings, but much of the older data is derived from an average of high and low waters, or mean tide level (MTL). This is covered in more detail in the case study in chapter 5.

Our current understanding is that over most of the 19th Century the rise in global sea level appeared to be close to zero, rising to an average of just over 2mm/yr during the 20th Century, and rising again to an average of 3.4 mm/yr in the 21st Century so far. The average global acceleration over the entire period is slightly above 0.01 mm/yr2 based on the most recent studies. However, as will be shown, there has not been a smooth change in rate through the 20th Century.

Section 2.1 gives a brief but comprehensive overview of some of the oldest surviving sea level records and why they were made, in a global context. This shows the extent of early observations, and the potential for data archaeology to make this data useful. This sets the scene for the introduction of details of early UK sea level observations and the first automatic tide gauges. Emphasis is given to metadata, or how sea level observations need to be referenced to fixed points on land in order to be suitable for long term sea level studies, and this leads to a discussion of early bench marks and the term “mean sea level”. This leads to an overview of early precision surveying and national land levelling campaigns, and the importance of the network of “permanent” bench marks and the relationship with sea level. Section 2.2 then discusses the importance of tide gauge calibration in the context of long term studies, and some early methods of countering instrumentation errors. Section 2.3 then brings this review up to date, starting from the early 20th Century, and how data from tide gauges once more became important towards the second half of the 20th Century with increased awareness of the potential impact of anthropogenic changes on climate. Section 2.4 the details how this perception changed through the two centuries of measurement as more data accumulated, and this leads to the current state of the art in section 2.5, with section 2.6 discussing the current understanding of the various drivers of sea level variability globally and regional differences, focussing briefly on the UK before expanding again to a global overview in the summary in section 2.7.

2.1 Brief overview of early work on measurement of sea level

A comprehensive historical review of work on tides before the 20th Century can be found in Harris (1898), and the history of modern tidal theory has also been well covered (Cartwright 2000, Pugh and Woodworth 2014). The scope of this review is limited mainly to historical observations of sea level, and focuses on observations that were systematically recorded in a way that allows us to relate these measurements to modern sea level. This requires some additional record (metadata) of the land based reference level used in the measurements.

2.1.1. Early observations around the world

In the Baltic Sea, where tides are small, there are several cases where the sea level was permanently marked by a carved horizontal line on stones or rock faces along with a date, for example Celsius' mark of 1731 (Celsius 1743, Ekman 2013), allowing these levels to be compared to modern levels. Where the ongoing millennial scale upwards vertical land movement in response to the removal of the weight of ice sheets during the last glaciation is highest, the changes of sea level relative to land level were obvious, even before such processes were fully understood (Lyell 1835). These old marks can be connected by levelling to modern datum levels, thus giving an estimate of the average rate of relative sea level change over the intervening time.

Figure 2.1: Image from wall of Western Camber, Pembroke Dockyard, showing XXV (25) foot mark of carved tidal scale, Ordnance Survey tidal bench mark of 1841, and HW level mark of 12th February 1899 (approx. 27.4 ft above scale zero). For comparison the highest HW surge between Nov. 1832 and May 1836 was 25.5 ft. Photo credit: David Pugh

In some regions close to sea level which have experienced high flood levels during extreme storm surges (Jensen and Müller-Navarra 2008), it was common to mark these high flood levels on buildings, or in some cases with permanent stone markers (Van Veen 1954, Fredriksson et al. 2018), the elevation of which can be connected to modern datum levels. Figure 2.1 shows a HW flood level mark for 12th February 1899, recorded as an exceptional high tide around the Bristol Channel (Anon. 1899) as well as an early OS bench mark, allowing this level to be connected to the national levelling datum. Where such marks were described by reference to historical mean high water levels, this gives a way of approximately connecting past mean and extreme sea levels to modern levels.

In regions where tidal variations are significant, port and harbour authorities had a vested interest in knowing and predicting the state of the tide relative to dock sills, the beds of tidal rivers and tidal bars (natural shoal ridges of sand often deposited just outside the mouths of rivers). Town and city planners needed information on high tides (and previous flood levels), whereas for safe navigation of coastal waters or in tidal rivers, knowledge of depth of water and state of the tide was necessary. Docks were designed and constructed with sill and coping levels set using observation-based knowledge of low and high-water spring tides as well as historical extremes, and in a few instances these early records were preserved (Talke et al. 2017). A fixed tide scale cut into the masonry of a harbour or dock entrance or a gauge fixed to a harbour wall not only allowed more accurate and consistent estimates of varying water levels to be made, but communicated this information visually to vessel owners. Some good early to mid-19th Century examples of stone cut scales can be found at the docks of Cardiff Bay, Albert Dock and the Salthouse Docks in Liverpool, Blackwall Basin in London, Portsoy, Maryport and Pembroke Docks (Fig. 2.1). Harbourmasters often recorded the levels of daytime high and low water as measured using these tide scales in ledgers. These records are invaluable, both for historical and modern tidal and sea level research. For obvious reasons dock tide scales often had their zero mark set at the level of the dock sill, and the dock sill became a fixed bench mark for the whole harbour or port. These dock or harbour datums were subsequently connected to local or national land based mapping datums by precise levelling, allowing historical measured sea levels to be connected to modern levels even if the original dock has since been destroyed.

In a small number of cases, sea level data with known datum information is available from before the start of the 19th Century, usually from established ports where historical height marks have been preserved directly or indirectly through levelling to surviving markers. In Amsterdam, sea level measurements were made in 1683-4, and around the same time the mean high water level was precisely recorded on several fixed stone markers (bench marks) at various points around the city (of which one still remains in its original location) and this level became known as Amsterdams Peil (AP). From 1700 onwards the sea level relative to AP was recorded daily, up to the enclosure of the Zuiderzee in 1932 (Van Veen 1945, Waalewijn 1987). The AP was transferred by levelling locally and then more widely around Europe (including Great Britain, using simultaneous observations at sites on either side of the English Channel) by the start of the 20th Century.

A small number of tidal observations from Brest (1679 and 1680), Bayonne (1680) and a few other sites were published, but only contained times of high and low-water (Picard and de La Hire 1680). The times and heights of high and low tides were recorded in a series of observations from June 1711 to September 1716 (records for 1713 were stated to be lost) at the request of the Academy of Sciences (de La Lande 1781). These observations were referenced to the stone scales at the entrance to the harbour. There is also a short series from August 1773 to June 1775, observed on the tide scales of the Brest basin, but the data from January 1778 observed on the same tide scales records high water only. A further record of daily high and low waters from January 1807 to 1835 (with some breaks), was published (Anon 1843). Monthly means of this data from 1807 are included as part of the PSMSL series. The series from 1711 has also been analysed (Cartwright 1972), and successfully integrated into a single composite time series (Wöppelmann et al. 2008). De La Lande (1781) also tabulates other 18th Century observations with both HW and LW referenced to fixed points from: Katwyk (Holland) for 1766; Rochefort 1771-1772 and Toulon from 1777 -1778 as well as tabular summaries of several years of observations from Calais, Dunkirk, and Graveline from which MTL could be derived relative to the port tide scale in use at the time.

Another long sea level series is available from Stockholm where systematic records of the water level either side of sluice gates (built in the 17th Century to regulate water flow between Lake Mälaren and the Baltic Sea) have been kept since 1774, the original levels being observed on scales cut into the stone walls of the sluice gates. These records have since been analysed and adjusted for small systematic errors (Ekman 2003, 2009) to create what is currently the longest quality controlled sea level time series in the World.

Elsewhere in the Baltic, we have data from 1811 onwards at Swinoujscie (formerly Swinemünde) which has been quality controlled and is available from the PSMSL. This author has also extended the historical annual data from Memel (Klaipėda) and Pillau (Baltiysk) back to 1811 and Colbergermünde (part of Kolberg or Kolobrzeg) back to 1816 through a previous data archaeology exercise (Hogarth 2014), although this data remains preliminary. Data published in the 19th and early 20th Century averaged over several years also exists for Neufahrwasser (Nowy Port, Danzig or Gdansk) back to 1815, Elbing (Elblag) back to 1812, and Königsberg (Kalininsgrad) back to 1819.

There is also a small amount of early 19th Century data from outside Northern Europe where original datum levels were recorded (Fig. 2.2, numbers in brackets in the following text refer to sites in the figure). These include (1) Boston MA from 1825 on the East Coast of the US (Talke et al. 2017), (2) Calcutta (Kolkata) from 1806 through to the 1820s (Kyd 1833), although this is a tidal river site approximately 120 km from the Ocean, (3) Madras (Chennai) from 1821 (De Havilland 1834) although there are unresolved datum issues with this site, and an extensive record from sites at Provincetown, (4) Cape Cod from 1833, 1834 and 1835 (Graham 1838), although it is doubtful that the original jetty level survey marks have survived.

Most early published sea level measurements do not give details of the reference point of the tide scale and all are manual observations. The following list is not exhaustive, but gives some idea of the global scale of tidal observations. For example hourly observations of rise and fall of the tide are given for Plymouth in 1668 (Colepresse 1668). It is unclear if these represent a single tidal cycle, or if they are averaged over many observed tidal cycles, but no reference datum is given. Similar records are presented of the mean rise and fall of the tide in the Hong (Hung) Road near Avonmouth, four miles below Bristol (Sturmy 1668). These early observers described a difference in diurnal tides, providing evidence used by researchers such as Newton in his Principia of 1687 (Newton 1846, Airy 1845b), and also suggesting that such observations covered longer periods than single tides. Over time observations of tidal range and times of “high water full and change” (*common establishment* or mean time between the upper or lower transit of the full or new moon and the next high water) were collected for sites around the world, and these were catalogued and published as aids to mariners. Only rarely were the individual observations published, one example being 9 days of rise or fall of the tide, and four days of hourly daytime rise or fall from (5) Kirkwall, Orkney (Mackenzie 1749). Voyages of exploration and scientific investigation also included tidal observations from remote sites in their records. Tidal measurements were made in 1761 at St Helena (Maskelyne 1762), Cook’s several voyages included tidal measurements which have been found to be accurate in terms of range to around 15cm (Woodworth and Rowe 2018) from locations including Tahiti in 1769, Charlotte Sound in New Zealand in 1773, and Tierra del Fuego in December 1774. High quality sea level observations using a portable gauge were published from a round world voyage between 1817 and 1820, giving tables of ten minute readings, and deriving an average sea level (niveau moyen) at several sites including (6) Rio de Janiero in January 1818, (7) Port Louis Isle de France (Mauritius) in June 1818, (8) Isle de Rawak (off Papua New Guinea) in December 1818, and (9) Guam in April 1819 (Freycinet 1826). Day and night-time manual observations of low and high Arctic water levels were recorded from

May, June and July of 1820 using a tide pole through a hole in the ice at (10) Winter Harbour, Melville Island (Parry 1821), and October 11th 1821 to May 16th 1822 at Winter Harbour, and November 18th 1822 to April 19th 1823 at (11) Igloolik (Parry and Hooker 1825). Manuel Johnson recorded high and low waters at (12) St Helena from at least October 1826 to the end of October 1827 (Cartwright et al. 2017). Observations of HW and LW at (13) Sitkhoe (Sitka) in July 1827, (14) Petropaulofsk (Petropavlovsk) in October 1827 and June, October and November 1828, (18) Port De Lloyd in May 1828, Bay of St. Croix in September 1828, and (19) Port de la Coquille in December 1828 by Lütke are tabulated by Whewell (1840b). The data from Petropavlovsk reads downwards on the gauge, whereas the observations at the other sites are given in the more conventional upwards direction, suggesting that despite the lack of published metadata these observations were referred to local tide scales or dock reference levels at the time.

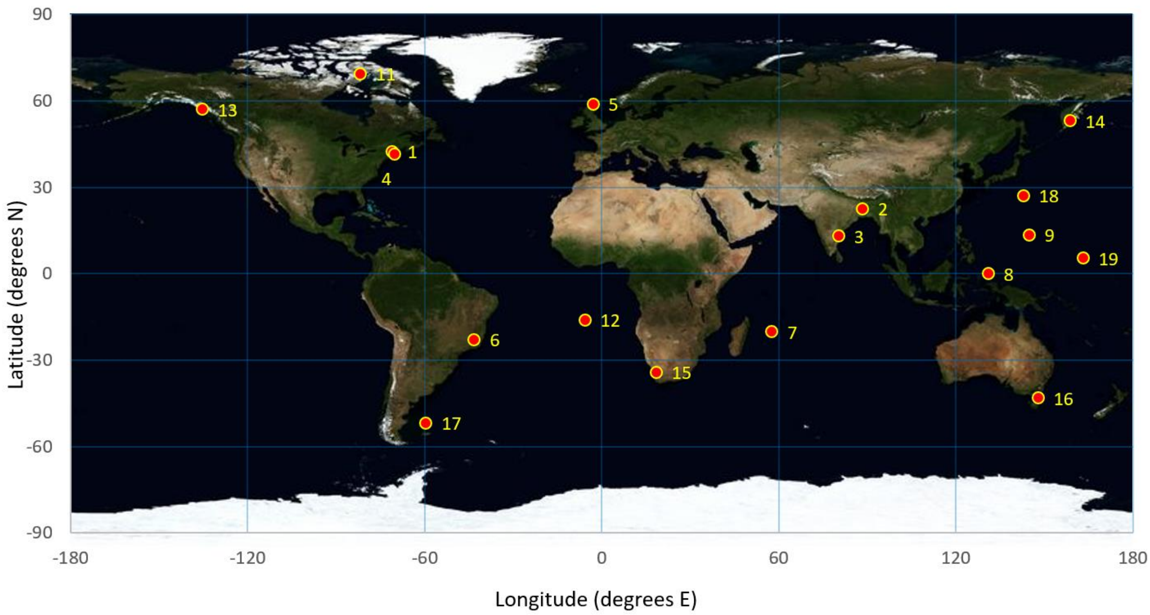


Figure 2.2: locations of some of the very early tide gauge records (pre-1830 in many cases) outside Europe and the UK mainland showing the widespread global distribution of potentially valuable observations. Base image courtesy of NASA.

Similarly we have data recorded from the 8th to the 28th June 1835 at 668 sites (28 on the American Coast, 2 in South Africa, 101 along the Western coast of Europe from Spain to Norway, 318 around the UK and 219 from Ireland) in a coordinated transatlantic effort inspired and reported by Whewell (1836b) following an earlier exercise in 1834 around the coasts of the UK and Ireland (Whewell 1835). Without a recoverable datum level the use of any of this data is limited to studies of tidal ranges and times. We also have monthly mean tide level from six months observations on a temporary gauge in (15) Simons Bay, South Africa (Anon 1837), and mention of further data from this site referred to specific dock coping levels. A letter of 1850 from Maclear at the Cape Observatory to the Admiralty (Maclear 1850) referring to the 1840 to 1848 readings from the Naval Yard, Simons Town (Findlay 1893) states "*I am well supported by Mr. Mann: his clear methodical head has waded through eight years of tide gauge diagrams*". This datum information may be recoverable using the Admiralty Datum Ledgers stored at UKHO Taunton, UK, provided the dock structures mentioned have survived. This would be a valuable addition to the sparse early records for the South African Coast, adding to our knowledge of the South Atlantic, along with the recovery of observations in 1841 from (17) Port Stanley in the Falkland Islands (Woodworth et al. 2010) from the expeditions of James Clark Ross to Tierra del Fuego.

2.1.2. Bench marks and the use of mean sea level as a geodetic reference level

It did not become routine to set up permanent markers as reference points for these remote tide gauge measurements until just before the mid 19th Century (e.g. Ross 1847), following on from directions from the British Association for the Advancement of Science (Anon 1836a, Denham 1836). It is believed that the first such benchmark was cut at the "Isle of the Dead" near (Fig.2.2, site 16) Port Arthur, Tasmania on 1st July 1841 (Pugh et al. 2002, Hunter et al. 2003) and the recovery of some of the detailed records (Lempriere 1837-1842, Lempriere 1840) provides us with one of the earliest accurate measurements of sea level from the Southern Hemisphere. The so called "debate" in the early 21st Century about whether this bench mark represents MSL, primarily due to confusion about the reference by Ross of establishing marks to "*mean level of the sea*" is easily resolved by noting the description of a tablet which was placed next to the mark "*On the rock fronting this stone a line denoting the height of the tide now struck on 1st July 1841, mean time 4H 44M pm; moon's age 12 days; height of water in tide gauge 6 ft. 1 in.*" (Shortt 1889). Examination of the original records shows that MHW as measured on the Port Arthur gauge was indeed around 6 ft above the Tide Gauge Zero. To date this author has only found one reference (out of thousands) to a mark physically set at MTL (by De la Beche during the "Geological Survey", at that time part of the Ordnance Survey of the UK) at Tenby in 1841 (Philips 1869). As De La Beche himself states (referring to MTL): "*marks on the coast itself at the actual level found may be in time obliterated from the action of the sea or atmospheric influences*" (De La Beche 1851).

From Mark	*Branch Levelling.*			
No. 150.	Copped-hall Railway Bridge. Mark on top of keystone at West side ; 1·73 ft. below centre of road - - - - - - - - - - - -	15,605	23·699	Pembroke 38
No. 150.	St. Issell's Church. Mark on South side of tower ; 1·38 ft. above surface - - -	10,135	72·152	„ „
No. 153.	Tenby Pier. Bolt in coping ; 21·34 ft. above Sir H. De La Beche's bolt in Pier Head -	- -	21·278	„ „
No. 155.	Mark on pavement at Mr. Yea's door, North side of High-street, Tenby - - -	- -	89·466	„ „
No. 156.	Penally Church. Mark on North-west angle of tower ; 1·89 ft. above surface - -	9,265	62·954	„ „
No. 157.	Tenby Church. Bolt in corner stone, at South side of tower ; 2·92 ft. above surface - -	5,130	94·123	„ „
No. 157.	Mark on kerbstone of footpath, at entrance to Mr. Richardson's stables, opposite the White Hart Inn ; 0·18 ft. above centre of road - - - - -	2,670	72·346	„ „
No. 159.	Gumfreston Church. Mark on North-east corner of tower ; 2·48 ft. above surface - -	2,105	78·186	„ „
„	Mark on rock inside gate, near Tar farm-house, South side of road - - - -	- -	96·084	„ „
No. 169.	„ on base of old cross, near Turnpike-gate at Carew Bridge ; 5·82 ft. above centre of road	5,900	45·378	„ „

Figure 2.3: Description of the OS bench mark on Tenby Pier, listed as 21.278 ft ODL, and described as 21.34 ft above De La Beche's copper bolt in the Pier Head. Clearly his bolt was set at MTL as observed in 1841. Source: Abstract of Levelling from Gloucester to West Angle Bay, through Newnham (James 1861a pg. 516)

The use of mean tidal levels as a geodetic reference point, combined with some fixed and stable reference point on land, are the two main requirements which allow older tidal measurements to be linked to modern measurements. The adoption of MTL began early in the 19th Century, due mainly to longer term practical considerations.

"*All barometrical observations on the sea-shore ought to be calculated from half-tide, and not from high or low-water mark, because the first is invariable, but the last two vary, not only according to the moon's age, but still more half yearly at the equinoxes*" (Strickland 1812).

This point was earlier hinted at by Hutchinson (1791) with regard to the tides at Liverpool. This is important for long term studies of sea level, as surveyors now required routine measurements of LW to be recorded as well as HW, allowing MTL to be estimated. Many previous series of tidal measurements were of HW only, such as the long series from the London Docks analysed by Lubbock (1830) and the series from Leith from 1827 to 1840 analysed by Whewell (1842). The record at Leith was reported as starting in 1806-7, but the early tide books were reported as lost in the 19th Century (Smyth 1866). The recording of HW was obviously important for land based civil engineering at the coast or on tidal rivers, and many city or town datums used by local authorities were based on such historic records (Talke and Jay 2017).

By the 1820s and 1830s barometric height and land survey measurements by some Admiralty and other prominent surveyors were often being made referenced to half tide (or MTL) (Sabine 1823, 1824, Howard 1828, Beechey 1832, Lloyd 1830, Bailey 1833, De

Havilland 1834, Bégat 1839, Stevenson 1842), although the term "mean level of the sea" was occasionally used with reference to MHW (Playfair 1798, Bevan 1821) or MLW (Mudge and Colby 1811, Squire 1821, and see Daniell 1826) until "mean sea level" became a more widely established and well defined term in the second half of the 19th Century. Lloyd, in his influential account of levelling between Sheerness and London Bridge (Lloyd 1831), set up a tide gauge at Sheerness and set the zero of his gauge to MTL. The subsequent modification of this gauge along the lines of a design by Palmer (1831) resulted in the first self-registering tide gauge in the world (Anon 1832). The hand written tidal ledger entries from Sheerness record the water levels referenced to both the tide gauge zero (approximately MTL) and also to the zero of the stone tide scale at the dock entrance. The merits of using mean tide level as a survey reference and measure of the true ocean level were argued by Naval surveyors (Walker 1846, Denham 1836) as well as influential scientists working on tide (Whewell 1837, 1839, 1840, Airy 1843). Lloyds survey methods, including the setting of bench marks locally, connecting them to further marks set in stable bedrock, levelling in both directions at each stage, and reference to the mean of a long time series of sea level measurements to determine a local vertical datum became a standard for future survey operations. These included Bunts levelling from Axmouth to Wick Rocks to determine how the MTL of the English Channel related to the MTL of the Bristol Channel (Whewell 1838a), and the later mapping operations of the Ordnance Survey.

2.1.3. The role of the Ordnance Survey, the Admiralty and national mapping efforts

The first geodetic levelling of Great Britain by the OS, which commenced in 1841, used an estimate of mean sea level at Liverpool, referenced to the "Old Dock Sill", as the zero reference elevation for the entire country. This level, transferred by precision levelling across the UK, became Ordnance Datum Liverpool (ODL). As part of this survey, a set of sea level measurements was taken in 1859 at various points around Great Britain. Although mostly only recorded for a fortnight, the mean of daytime sea level observations taken every ten minutes over a complete tidal cycle each day were then averaged to give MSL for that site, as well as the mean of high and low waters (MTL) (James 1861a, Woodworth 2018). The Second Geodetic Levelling between 1912 and 1921 used MSL at Newlyn between 1915 and 1921 as the national mapping datum or Ordnance Datum Newlyn (ODN). Similar national mapping exercises in Europe, the US, India and parts of Asia through the second half of the 19th and early 20th Century meant that geodetic connection was made between tide gauge reference points and local bench marks which were part of national mapping networks using precision levelling (Rappleye 1938). This meant that not only could water level readings be compared between sites some distance away, but that readings could be compared at the same location over time, referenced to a consistent land based datum surface defined by many levelled bench marks which could survive the destruction of any one mark.

The reference zero level for all nautical charts however remains as some definition of low-water up to the present day, for example the UK Admiralty used local Low Water Spring Tide (LWST) in the Admiralty Tide Tables (ATT) up until the late 20th Century, when in most places it was changed to Lowest Astronomical Tide (LAT). These local LW datums were connected through Tide Gauge Bench Marks (TGBM) to the National land mapping datum in many parts of the world (Airy 1845a, Cutts 1877, Thomson et al. 1879, Eccles 1901).

In the UK, for parties seeking to charge rates associated with any new dock or harbour to be constructed, the Harbours, Docks and Piers Act 1847 included a statutory requirement for installing and maintaining a self-registering tide gauge and barometer and sending monthly results to the Admiralty (clause 18), allowing them to construct more accurate tide tables. By the second half of the 19th Century, relatively low cost automatic tide gauges were becoming available, making installation at port and harbour sites around the world more economically viable. By the start of the 20th Century such gauges were installed on the coasts of Alaska, South America, South Africa, Japan, Australia, New Zealand and around the Indian Ocean. Other gauges were installed temporarily to aid dock design and construction (Dobson 1899). Many of these records were archived and summaries of some were published, but only short published sections of early records survive (or have been found) from some regions, notably South Africa, South America and the tropical Pacific (Aucan et al. 2017).

2.2. Accuracy and calibration of tide gauges

Before the introduction of self-registering gauges, many tidal register table entries were read from tide gauges consisting of carved stone tide scales or painted tide boards, and readings to the nearest half or quarter ft. were often given. Standard Admiralty tide boards used in UK tidal surveys were marked with 0.25 ft (around 70mm) increments. Improved resolution can be gained by the process of averaging when using monthly means. More consistent individual readings could be obtained by using a gauge fitted inside a stilling well (in use since the 18th Century), allowing resolution of fractions of an inch (one inch is just over 25 mm) without interference from waves. Early self-registering tide gauges installed in the first half of the 19th Century were capable of much greater resolution, but as they were checked against harbour tide scales (as at Sheerness, discussed above and see Fig 2.4 below), the long term accuracy was limited. Over time the design of gauges improved, and interest in accurate metrology and long term changes in sea level made more precise calibration of the gauges desirable.

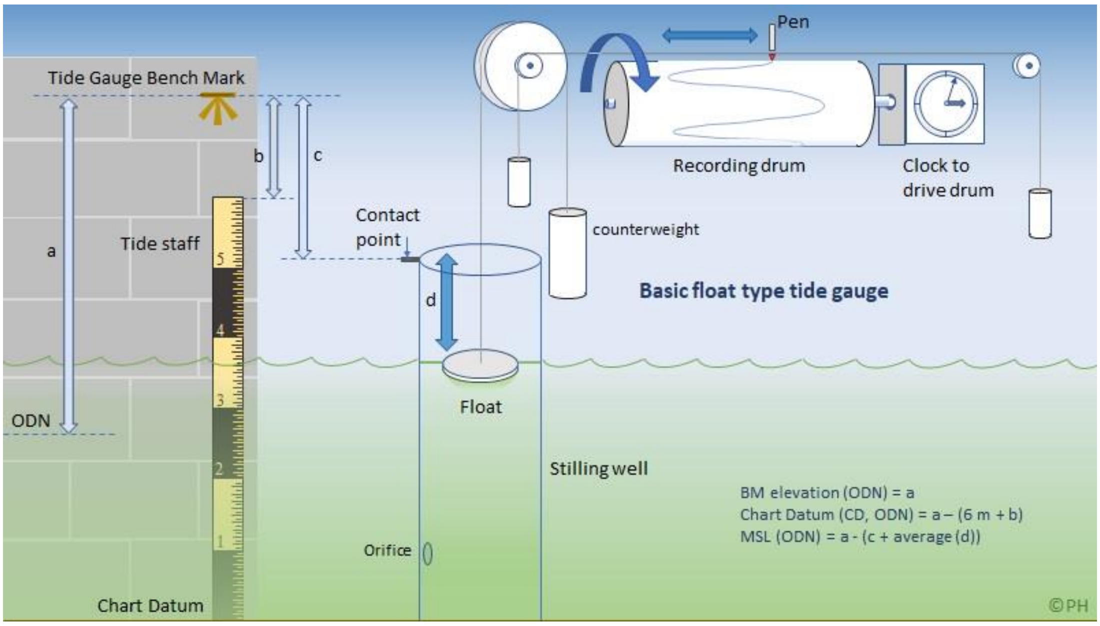


Figure 2.4: idealised diagram of a float type tide gauge from which the majority of current tide gauge records are derived. Functionally similar types of instrument were in use from the 1830s to the late 20th Century worldwide. The levelling connection to a stable land based reference point (as well as a standard manual tide staff) is shown. Here the land based levelling datum is Ordnance Datum Newlyn (ODN) as used throughout the UK.

The essential requirement for a stable measurement platform was appreciated from the earliest times, and the potential for subsidence was noted at Sheerness docks by Lloyd (1831) who pre-empted this possibility by setting bench marks on more stable ground some distance away. In another example the original 1854 to 1859 MTL record from Fort Point (the earliest section of the long-term composite record from San Francisco) was known at the time to be affected by jetty subsidence as given by repeat levelling between bench marks and the gauge. Adjustments for this subsidence were recorded on tabular tidal records from the 1860s and 1870s (Talke and Jay 2013, supplementary figure S7 and S8) allowing later re-interpretation and adjustment (Smith 2002).

Equally important was the calibration of the instrument itself for scale and various offset errors. Some of these error sources could be minimised by using longer recording drums and wider paper rolls, but this did not provide a means of correction. Thomson (1868) proposed using a metal gauge attached to a loose piston inside a vertical metal tube one end of which was below sea level. When the gauge is slowly lowered inside the tube and touches the water level an electric circuit including a "telegraph" detector is completed by the sea water, allowing a precision of water level measurement to the nearest 0.1 inch (2.5 mm). This is essentially the same electrical sounding system used in the UK tide gauge network until the second half of the 20th Century to calibrate float type tide gauges during a Van de Casteele test, (see appendices) although the mechanical gauges themselves (which had changed little since the late 19th Century) have other systematic error sources which prevent measurement accuracies of better than around 1 inch (25mm) (Lennon 1968, 1971). Other methods of tide gauge calibration were also in use by the end of the 19th Century. Russell, who took over the Sydney Observatory from Smalley in 1870, found that the automatic tide gauge first installed at Fort Denison by Smalley in 1867 was prone to errors caused by the hempen cord connected to the gauge float stretching and varying length with the weather (Russell 1885). In June 1872 he replaced the tide gauge with a more reliable one using a chain, and the chain length was frequently measured to allow for wear, breakage and stretch. These measurements were then subtracted to adjust the sea level observations to a constant datum level. This accounts for the differences of up to 300mm (around 12 inches, see below) between tables of annual Sydney MTL reported by Darwin in the UK (Darwin 1888), later finding their way into the PSMSL ancillary time series (Spencer et al. 1988) and the corrected values from the same gauge for the same years reported by Russell in 1885. Further evidence that the published records were unadjusted is reported by Knibbs (1888) as shown in the extract below.

FIXATION OF MEAN HIGH-WATER MARK.

THE following information, obtained by compilation from the published record of the self-registering tide-gauge, at Fort Denison, will be of value to surveyors engaged in fixing the position of the mean high-water mark in Port Jackson :—

Mean of all high tides,	1881	to	1886	49.9	inches	
Mean of all low tides,	,,		,,	10.3	,,	
Mean sea level	,,		,,	30.1	,,	
Mean range	,,		,,	39.6	,,	
Highest tide	,,		,,	80.0	,,	
Lowest tide	,,		,,	13.0	,,	below zero

The above are the readings on the Fort Denison Gauge. It should be particularly noticed that 12 inches should be *subtracted* from the present readings of the gauge, the zero having been altered by that amount owing to the alteration in the length of the chain carrying the float ; and when making enquiries at the Sydney Observatory *the relation of the zero of the gauge records to that of the published records should always be ascertained*, as the chain having been broken and repaired on several occasions has been each time altered in length.

At the present time the amounts recorded above, if increased by 12 inches, would be immediately comparable with the gauge records ; but as the published amounts are reduced to the original datum, it is preferable to apply the correction as suggested.

12th September, 1888. GEO. H. KNIBBS.

Figure 2.5: Extract from "The Surveyor" or Journal of the Surveying Club from 1888, Sydney, NSW, Australia. Around this time the different zero level datums in use by various local authorities in Sydney were being consolidated.

The Thomson ("Kelvin") gauges installed in ports controlled by Japan in the late 19th Century were calibrated by periodically raising the tide gauge float up so that the bottom of the float was level with the top of a board fixed some way above HW level which was a known vertical distance from a levelled bench mark. This process marked the gauge record with a line so that when the float was lowered back to the water surface, the length of line on the paper record precisely reflected the distance between the top of the board and the sea surface, minus the known water level on the float body relative to the float base (Hirayama 1911). Again this allowed adjustment for float wire stretch or instrument related datum changes through time.

Clearly it is important to know if documented records have been adjusted or not if we are investigating long term changes using these records. This highlights the critical need for the preservation of associated tide gauge metadata (e.g. as published by Hirayama) even for modern tide gauges.

2.3 Sea Level measurement through the 20th Century and beyond

Gradually, tidal theory and the use of mechanical tidal prediction machines allowed estimates of every high and low water for a year or more to be computed and published in advance for every port and harbour where prior observations were available. The time to produce such predictions using machines was greatly reduced compared to using human computers. In territories controlled by the UK, for financial reasons (whilst the national economy stagnated after the post First World War boom), increasing reliance was placed on tidal predictions based on harmonic analysis of historical records, and many tide gauges fell into disrepair or were discontinued. By 1925 only 8 out of 43 sites in the Survey of India, mostly set up in the 1880s and 1890s, still had operating tide gauges (SOI 1928). In other regions where trade was increasing, such as in the US, even the depression of the 1930s did not prevent a steady increase in the number of tidal stations (USCGS annual reports 1920-1938, available from https://library.noaa.gov/Collections/Digital-Collections/USCGS-Annual-Reports) where data was gathered and processed.

Whilst trade depended on safe navigation between sea ports and along coastal routes, and vessels tended to become larger over time, knowledge of depths and tidal regimes was essential. The authorities responsible for generating nautical charts (for example the Admiralty in the UK, and the USCGS) required detailed tidal measurements which were periodically updated prior to the generation of new charts. The results of tidal observations, summarised in table form on the charts, gave a local LWST zero reference for the chart soundings, and importantly referred this reference to a local land-based bench mark.

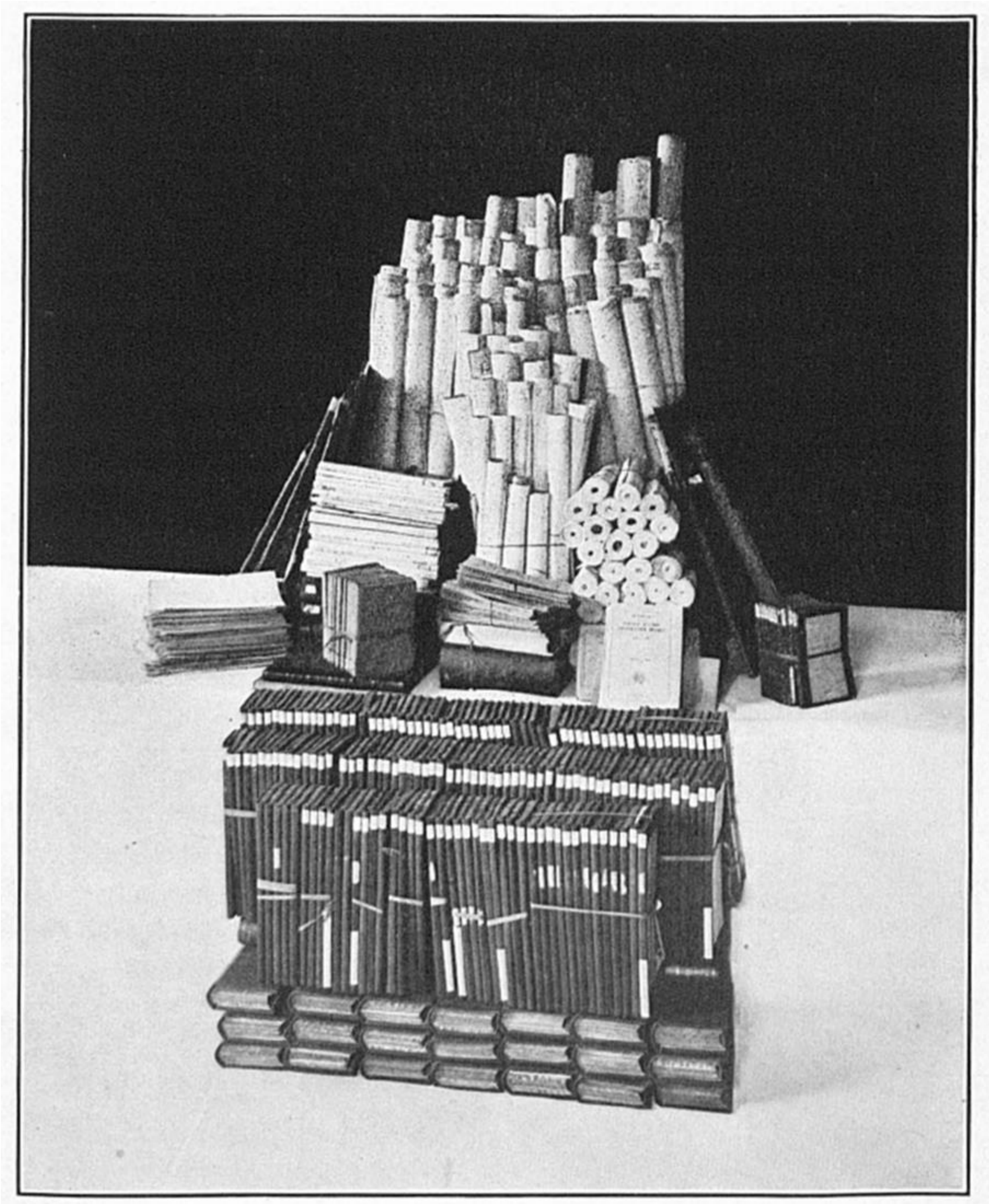


Figure 2.6: Photograph exhibited at the 1926 Exposition at Philadelphia showing the 469 field survey sheets, sounding and tidal records and volumes of data required to supply information for the production of a single chart (USCGS Annual Report 1926) image courtesy NOAA.

Sea level along coastlines and at island sites around the world has been well monitored by tide gauges (TG) since the mid-twentieth century, with Sea Level Rise (SLR) being observed at almost all sites once vertical land motion is accounted for. In Europe, the need for properly maintained national tide gauge networks was emphasised after the storm surge and high tide of 1953 (Rossiter 1954) caused coastal flooding, particularly in the UK and the Netherlands, leading to the loss of hundreds of lives. Since 1993 geocentric SLR over the entire global ocean surface has been measured by a succession of overlapping satellite altimetry missions, showing ongoing SLR and emerging evidence of acceleration over the past 27 years (Kleinherenbrink et al. 2019; Veng et al. 2020). It is important at this point to appreciate that there are differences between coastal observations using tide gauges, and satellite based radar altimetry sea surface height measurements (Woodworth et al. 2019). The most fundamental of these is that all historical tide gauge measurements are relative to land based vertical reference points (i.e. RSL), and thus to make them compatible with satellite observations in terms of regional or global SLR trend we need to account for any vertical land motion such as GIA in the same geocentric reference frame. This can be achieved using GNSS to monitor vertical movement at the tide gauge, or using global or regional GIA models, or using the overlapping periods of satellite data and tide gauge data and estimating any linear trend differences. These techniques will be discussed later in chapter 3.

Using the coastal tide gauge observations, estimates of the rate of sea level rise has varied over time, depending on the span used. The varying start and end dates explain much of the difference in reported values (Douglas 1992, Hogarth 2014) and this is explored in section 2.4. Several global and regional analyses have used the more sparse set of long TG records, and the longest records available (Woodworth 1990) show an acceleration of around 0.01mm/yr^2. The records that stretch a few decades back into the 19th Century are concentrated in the Northern Hemisphere which can bias global estimates (Natarov et al. 2017). The results of data archaeology (Hogarth 2014), where annual mean sea level data was extended into the 19th Century for a large number of global sites, have been used to show that extending data series results in reduced inter-site variability and trend differences globally. Clearly, recovery of more old data (Caldwell 2012, Marcos et al. 2020) and metadata will further improve existing records and lead to a more detailed picture of spatial and temporal sea level variations. Progress is being made. As well as studies mentioned above, a two century long composite record (back to 1824) has been recovered for Pertuis d'Antioche on the Atlantic NW coast of France (Gouriou et al. 2013). The record for Boston MA on the Eastern US coast has been extended back to 1825 (Talke et al. 2018), whilst for Astoria on the Pacific US coast the record has been extended back to 1853 (Talke et al. 2020), adding to the existing record from San Francisco which starts in 1854. The record from Marseille in the Mediterranean has been extended back to 1849 (Wöppelmann et al. 2014), whilst efforts are ongoing to reduce the 1858 onwards record from Williamstown, Melbourne in Australia to a consistent datum (McInnes, 2020 reported in Bradshaw et al. 2020). Many of these studies have focussed on digitisation of long paper mareogram records or tabular daily records from single sites and have involved a huge amount of manual effort. This is ongoing and painstaking work. This thesis shows that even short periods of data can also be valuable provided the volume of data is high enough and tide gauge datum metadata is available.

2.4 Historical changes in perception of sea level, sea level rise and acceleration

The literature review here is again far from comprehensive, but is intended to give some context for the research project and the justification for a need to ask the underlying research question "*Is the rate of coastal sea level rise accelerating?*" The current understanding is that global open ocean sea levels as estimated from satellite altimetry 1991 to 2021 are rising, with current SLR estimated to be 3.5 mm/yr, and accelerating. The SLA from ESA satellite missions covering 1991 to 2019 over latitudes between ± 82° is estimated to be 0.095 ± 0.009 mm/yr^2, whilst the Topex and Jason NASA satellite missions give 0.080 ± 0.008 mm/yr^2 for the 1993–2019 period over ± 66° latitude (Veng at al. 2021). Considering the century scale records available from coastal tide gauges, the longer term acceleration from the late 19th century onwards is smaller, of order 0.01mm/yr, although the value depends on the period and sites selected.

2.4.1 Early views on stability of sea level

As discussed in part 2.2, early long range levelling exercises carried out for mapping purposes starting in the mid to late 19th Century and continuing in the 20th often involved sea level measurements, as by this time mean sea level had been established as the reference for many national land mapping datum systems (Anon 1894). These measurements seemed to indicate significant and seemingly consistent differences (at several decimetre scale) between mean sea level at different locations separated by a few hundred km (Ravenstein 1886). In addition, as sea level records got longer, the idea that the mean sea level was fixed at any location (at least in historic times) relative to a stable land mass (Beulig 1935), began to be questioned. This was set against a growing realisation through the second half of the 19th Century that sea levels had altered by perhaps hundreds of metres during glacial periods (Tylor 1869). In the 1920s and 1930s, the apparent increase in sea level compared to that of the 19th and early 20th Century gave rise to debate about whether current regional mean sea level was increasing or land levels were sinking (Lallemand and Prévot 1929). Discussion tended to be between academic geologists (Johnson 1917, Johnson and Winter 1927) who took a longer term view encompassing very large changes related to the previous ice age, and sea level experts and surveyors within the USCGS (Schureman 1936, LaFond 1939) and other surveying authorities such as the OS (Close 1923) who looked at the small decadal changes being measured by their instrumentation. Several sea level observers were also noting the connection between sea level and sea temperature at seasonal scale (Nomitsu and Okamoto 1927).

2.4.2. First half of the 20th Century: Decadal scale acceleration

In a comprehensive global study of sea level variation and relative land movement at the start of the 1940s, Gutenberg showed that the rate of sea level rise as measured at most tide gauges using data from 1807 to 1937 had increased in the decades up to the 1930s (Gutenberg 1941) and it was suggested (Thorarinsson 1940) that this was linked to qualitative or at best crude quantitative observations of widespread loss of glacier mass (Matthes 1936). By the end of the 1940s, this increase in observed SLR had continued, at least on the mainland US coastline (Marmer 1948, 1949) and the existence of extensive ice mass loss in all regions where it was monitored (which at that time excluded Antarctica) over the previous few decades was accepted as fact (Ahlman 1949).

Ahlman states "*If the polar inland ice sheets should begin to melt as rapidly as the other glaciers, the rising sea-level would become a phenomenon of great and far-reaching practical importance*".

By the 1950s the increase in SLR at the majority of coastal sites seemed beyond doubt (Marmer 1951) and multi-decadal ice mass loss from glaciers and Greenland was strongly implicated (Field 1956) and related to observations of rising global temperature since the end of the 19th Century (Willett 1950). In the early 1960s, in a study using carefully selected tide gauge sites, a global sea level curve was constructed over the period from 1860 to 1960 showing a clear positive acceleration (Fairbridge and Krebs 1962, Fig. 9).

These last authors' tentative link of this change to variation in sunspot numbers following work such as Lawrence (1950) is now known to be spurious (Shaw 1965) due partly to the difficulties of confirming correlation and decadal periodicity when analysing relatively short time series where time correlated (coloured) noise is evident (Moore et al. 2006, Brugnara et al. 2013, Gil-Alana et al. 2014). Love (2013) is particularly instructive in this respect. However, in a study of global temperatures from the same year (Mitchell 1961) updating that of Willett it was shown that the observed increase through the first half of the 20th Century had levelled off after the 1940s and then fallen slightly by the end of the 1950s.

2.4.3. Second half of the 20th Century: Sea Level Rise confirmed, but no acceleration?

In a study of US gauges using a shorter span of 1940 to 1975, where an average curve using data from all gauges was constructed, acceleration was also evident (Hicks 1978). However, by the 1980s what is now recognised as a slow-down in observed global SLR in the 1960s (decadal scale deceleration, see section 2.5) had reduced the reported average long term acceleration value to close to zero (Gornitz et al. 1982). In addition, the lack of systematic adjustment for vertical land motion or GIA in previous studies led to the suggestion that mean sea level was not rising, but rather the arbitrary selection of geologically "stable" sites avoiding known areas of post glacial uplift might give an apparent SLR (relative to the land) due to bias caused by sites where coastal land levels were slightly subsiding (Pirazzoli 1986). By the start of the 1990s however, Douglas (1991) had confirmed an average global geocentric sea level rise of around 1.8mm/yr between 1880 and 1980 following the availability of early versions of the Peltier GIA model, ICE-3G (Tushingham and Peltier 1991). In parallel, the first comprehensive global estimates of mean temperatures showed a resumption of rapid surface warming from the mid-1970s, as well as finding no significant trend through the 19th Century (Jones et al. 1986).

Influential papers by Woodworth (1990) looking at European tide gauge data and Douglas (1992) using global data then directly addressed the question of acceleration in sea level, and concluded that acceleration was not yet evident over most of the 20th Century. After observed SLR began to rise more rapidly again during the early 1990s, (Holgate and Woodworth 2004) many studies looking at the increased span of data available once again reported statistically significant acceleration in the globally averaged records (Church and White 2006, 2011, Woodworth et al, 2009b (see Fig 4)), and also in most of the longest records, whilst other studies found little or no evidence for acceleration (Wenzel and Schröter 2010, Houston and Dean 2011, Watson 2011) over spans of at least 60 years. At the same time analysis of the major physical contributors to sea level rise suggested that based on global temperature and land based ice mass changes over the most recent decades, sea level acceleration should be anticipated (Rignot et al. 2011) even if not already evident.

For a time this apparently conflicting evidence for sea level acceleration led to the so called "acceleration/deceleration debate" (Baart et al. 2012, Houston and Dean 2013, Visser et al. 2015). As shown later in this section this apparent discrepancy between SLA values derived from similar tide gauge databases can be largely reconciled, and the issues of multidecadal variability and drawbacks and advantages of approaches used in previous analyses are well illuminated by Haigh et al. (2014).

2.4.4. Current assessment: Persistent acceleration

Comprehensive studies since this time, looking at global sites and the longest time periods, have confirmed an ongoing increase in SLR (Hogarth 2014, Haigh et al. 2014, Hay et al. 2015, Dangendorf et al. 2017, 2019, Palmer et al. 2021, Houston 2021) and emergence of persistent acceleration through the late 20th and 21st Century to date. The most recent of these (Houston 2021) gives 0.0128 ± 0.0064 mm/y^2 for 129 high quality tide gauges around the world with records exceeding 75 years, which is similar to the acceleration derived in other studies e.g. 0.011 mm/yr^2 for the data from Dangendorf et al. (since 1900) if this is derived using a fitted quadratic trend, whilst the Church and White reconstruction (Church and White 2006, 2011) has recently been updated to 2019 (Wang et al. 2021, Legresy, B. pers. com. 2021) and gives an acceleration of 0.015 ± 0.003 mm/y^2 since 1880.

2.4.5. Influence of start and end date of analysis

An important overall conclusion is that regional and global sea level as measured from the earliest observations have not risen at a constant rate, and so derived long-term trends depend on the end date of the analysis, and thus to an extent on the date of publication (Spada and Galassi 2012). This allows these different previously published results using the same or similar global tide gauge data sets to be reconciled (Hogarth 2014), although some differences do remain and can depend on site selection, method of combining records, and methods of deriving trend estimates (Hamlington et al. 2015b). A related factor is that in general the uncertainty associated with any derived trend also reduces as the time span of analysis increases. It follows that we can have more confidence in estimates based on the longest series available (and again in general, studies published more recently) (Haigh et al. 2014).

Similarly, the *start* date of trend analyses also affects both average trend and uncertainty. A study of 12 sites on the Atlantic coast of North America shows significant acceleration between 1969–2011 (Boon 2012), and regional analyses of the Eastern Atlantic Coastline of Northern Europe shows robust positive acceleration values in the overlapping period between 1959 and 2018 (Hogarth et al. 2020a). Importantly, interannual variability (which might otherwise bias results over this decadal period) is reduced by accounting for the response of sea level to wind and atmospheric pressure as simulated using a barotropic (constant density) ocean model. Over similar timescales (the second half of the 20th Century and beyond), statistically significant acceleration is also seen in several independent global studies, including: Merrifield et al. (2009) using data from 134 global stations from 1955 to 2007; Dangendorf et al. (2019) using a similarly large global dataset between 1958 and 2018; and Calafat and Chambers (2013) using data from 9 regionally representative high quality global sites 1952 to 2011.

These last studies again make adjustments to the data to account for the effect of meteorological factors like wind and air pressure in order to reduce the interannual variability. This is a necessary step if robust trends are to be derived from the larger number of global MSL time series which are available from the second half of the 20th Century. One of the other reasons for selecting a limited and more recent time span in these sea level analyses is the parallel availability of high quality historical barotropic data. Reanalysis products such as ERA40 (Simmons and Gibson 2000) covering Sept 1957-August 2002 improve accuracy over what can be obtained purely from surface-based measurements by including radiosonde data to give 3-D structure to the atmospheric variations. This data is only available globally from the 1950s onwards (mainly after the International Geophysical Year 1957-8) whilst ERA Interim and the newer ERA5 (Hersbach et al. 2020) covering 1979 to date further improve data density, quality and consistency by also assimilating global satellite observations, which through successive missions have increased in accuracy and sophistication. Observation based ocean models of regional sea level variation such as CS3X (see chapter 3) are typically based on these types of reanalysis and thus obviously cover the same limited time spans.

The recent availability of a more robust historical re-analysis product, 20CRv3 (Slivinski et al. 2019) based on a greatly extended dataset of surface observations (covering a period from 1836 to now) improves the situation when analysing sea level data from before the 1950s (see case study in chapter 4), but the measurable reduction in overall interannual sea level variability (or the significant proportion of variability at the coast induced by regional meteorological effects) gets less as we move back into the early 20th Century and before. This is countered to some extent by a tendency towards reductions in formal uncertainty levels when longer time series are analysed.

If the start date of SLR analysis is moved further back into the first half of the 20th Century then the acceleration observed in the previous studies can weaken or reverse depending on the start date and sites selected, due to the slowdown in SLR in the 1960s noted above. A study of 30 tide gauge records from the Baltic and North Sea found no statistical acceleration when the length was limited to the period 1900 to 2012 (Hünicke and Zorita 2016), although most of the sites showed a weak bias towards positive acceleration. Similarly a study of 25 US records spanning 1930 to 2010 and global records from 1930 to 2007 (Houston and Dean 2011) also showed no statistically significant acceleration, but many showed weak deceleration. Importantly, the somewhat arbitrary choice of start date in these cases (as regional time series with earlier dates were available) defines the trend over the selected period (Rahmstorf and Vermeer 2011). In both cases, when trends are derived from the smaller subset of time series from the selected sites which extend back before the late 19th Century, these show significant (at the 1 sigma level) positive acceleration with lower uncertainty levels. This result tends to be consistent wherever longer time series are available globally (Hogarth 2014). It appears that at long enough (approaching 150 year) time scales, a common underlying acceleration of order 0.01 mm/yr^2 emerges which is large enough to be unambiguously detected against regional decadal scale variability, and this acceleration is therefore likely to reflect global scale long term changes. This long term acceleration is explored for the UK in chapter 5 by extending and densifying the tide gauge record. We will show that extending the SLR analysis to the 19th Century (where records permit) is particularly important for at least the North East Atlantic in order to capture a significant change in SLR gradient around the start of the 20th Century.

2.4.6. Sea level change estimates from salt marsh proxies

Longer proxy records of relative sea level can be derived from salt marsh cores, although these are often characterised by poor resolution both temporally and in elevation. The timescale of these records bridges the gap between instrumental records and ice core or geological records, and therefore can help to answer questions about rates of SLR prior to the industrial period, and whether current changes in SLR are unprecedented in the period since the end of the last glacial period. Some high resolution salt marsh records show good agreement with long tide gauge records and can show similar interannual variations (e.g. Brest, Rossi et al. 2011), and although several of the records do show changes in rate of SLR which are broadly consistent with existing tide gauge records over the past 200 years, there appear to be significant regional differences which have been ascribed to real regional differences in RSL (Long et al. 2014). Evidence from salt marsh proxies from the Eastern US suggests a similar pattern of sea level rise to existing long tide gauge records, (e.g. Boston from 1825 and New York from the 1850s) with little evidence of a change in sea level rise prior to the 19th Century, and a most probable change in rate of SLR somewhere in the broad intervals 1815–1957 (95% credible interval); compared to 1834–1922 from similar salt marsh data in NE Florida (Kemp et al., 2014) and 1830–1940 in W Florida (Gerlach et al. 2017). Some salt marsh proxy records from the northeastern US coast have been used to suggest that similar regional changes in rate of sea level as are currently evident from the instrumental record have occurred in pre-industrial times (Gehrels et al. 2020). Some caution is warranted as differences thought to be due to compaction rates can introduce apparent changes in estimated sea level rise, as shown by an example using two different records from adjacent locations near Long Island sound (Fig. 7 in Brain et al. 2017). Uncertainties in elevations due to the sediment depth transfer function can typically be between 10% and 15% of the spring tidal range (e.g. ±100mm for the Magdalen Islands in Canada and ±260mm for the Vesterålen Islands in Norway) (Barnett et al. 2017). These values are comparable with the seasonal variations in monthly mean sea level as recorded near these sites, but are only slightly larger than the combined uncertainties of the composite pre-1850 tide gauge data from the UK (although the combined uncertainties are most likely due to a combination of datum differences and imperfections in the GIA model used at different sites, and the variability seen at individual sites is much lower). Such salt marsh proxy records as have been studied in the UK have large uncertainties associated with them which makes it difficult to draw conclusions about SLR changes even at multi-decadal timescales (e.g. Fig. 7 in Barlow et al. 2014). It has been suggested from the available salt marsh proxy evidence that the changes in SLR towards the end of the 19th

Century are less evident on the eastern side of the Atlantic (Barlow et al. 2014), but a comparison of the newly extended (back to 1825) tide gauge record from Boston MA (Talke et al. 2018) with the existing long records from Europe suggests otherwise, with strong similarities at multi-decadal scale. This highlights the value of recovering long-term instrumental observations. Even so, these proxy records can augment the long records from Europe and the US discussed in section 2.2 (most of which show good agreement over at least the 20th Century).

2.5 Modern Outlook: The physical basis for sea level rise and acceleration against a background of natural variability

Sea level is known to be affected by several factors, which will be explored in more detail later in this section and in chapter 2.6. Not all of these drivers are climate related or anthropogenic (Frederikse et al. 2020). Terrestrial water storage can cause smaller natural sea level fluctuations at interannual timescales due to rainfall patterns over land, but a much larger and more long lasting effect is now known to have been caused by large scale dam building projects in the 1960s and 1970s, impounding sufficiently large volumes of water to cause an anthropogenic but non-climate related global slowdown in rate of sea level rise over the same period. Elevated levels of stratospheric SO_2 from major volcanic eruptions such as Pinatubo are known to cause a transient reduction in solar radiation reaching the earths surface, which has a negative impact on ocean heat content and steric sea level which may last for several years This is accounted for in most sea level models. Dust from atmospheric testing of nuclear weapons may also have had a similar but compound effect over the period between 1945 and 1980, with a peak before the limited test ban treaty of 1963 (Fujii 2012). There are also regional scale variations, for example the interannual to decadal scale ENSO related variations of opposite polarity on the East and West Pacific coasts (Hogarth 2014). These fluctuations are the coastal expressions of large scale water redistribution caused by variations in ocean basin scale currents and recurrent atmospheric pressure and wind patterns, but taken in isolation at a specific site, can lead to significant changes in local or regional sea level trend.

However the two dominant components of the global SLR budget, volumetric (steric) expansion and mass redistribution from melting land based ice are both driven by the currently ongoing planetary accumulation of thermal energy, represented by an increase in globally averaged temperatures in the world's oceans over most of the industrial period (Zanna et al. 2019). In brief, this net energy gain is caused by an imbalance between incoming solar radiation and outgoing long wave radiation at the top of the atmosphere (Trenberth 2020). This has now been confirmed by direct observational evidence (Kramer et al. 2021) and is controlled by several factors, including the concentration of non-condensing "greenhouse gases" in the atmosphere, and in particular the increasing levels of CO_2 from burning fossil fuels (from around 280 ppm in pre-industrial times to 415 ppm averaged over the year to May 2021) https://gml.noaa.gov/ccgg/trends/. The planet's surface is heated under the influence of solar radiation, around 99% of this energy is in the range 0.15 to 4 µm wavelength (peak energy being at the shorter blue end of the visible spectrum) where the atmosphere is effectively transparent. The Earth's surface, particularly the oceans (due to their much lower albedo), absorbs this incoming energy and re-radiates a proportion of it upwards as longer wave infra-red (IR) radiation (heat) between 3 and 50 µm wavelength. CO_2 (and other components such as water vapour) in the atmosphere absorb and re-radiate some of this energy at specific IR wavelengths (in all directions, half downwards). CO_2 has a distinct absorbance peak around 15 µm allowing its effect to be differentiated from that of water vapour. This results in a net warming of the earths surface, oceans and lower atmosphere above what would result if all of the IR radiation emitted from the surface were transmitted outwards to space unhindered. A plausible mechanism for transfer of IR radiative energy to OHC in the upper ocean layers, given that incident longwave radiation cannot directly heat the layers below the top fractions of a millimeter of the ocean surface, is presented in Wong and Minnet (2018). More than 90% of this additional thermal energy as measured since 1955 has accumulated in the oceans (Levitus et al. 2009, Cheng et al. 2017, Meyssignac et al. 2019, Johnson and Lyman 2020), and this increasing OHC and transport of energy polewards via ocean and atmospheric circulation strongly influences temperatures elsewhere on the earth's surface (Dieng et al. 2017, Cheng et al. 2019, Irving et al. 2019, Rohde and Hausfather 2020, Cheng et al. 2021). Some studies show ocean warming appears to have started at the turn of the 20th Century (Xu et al. 2021) whilst an array of paleoclimate studies shows that a change from a gradual long term global cooling trend over the past two thousand years to a significant and relatively rapid warming trend occurred around the mid to late 19th Century (Abram et al. 2021). The increase in ocean heat content since the ocean observational network achieved near global coverage in the 1950s is one of the most reliable indicators of planetary energy imbalance (Meyssignac et al. 2019, Allison et al. 2020). This can also be inferred from the associated major component of sea level rise due to thermal expansion over the longer tide gauge observational period.

The non-linear pattern of low SLR in the 19th Century, followed by a rise in rate around the late 19th or early 20th, then a slowdown in the 1960s, followed by more sustained rise after the 1990s (to around 3.4mm/yr 1993 to 2021 derived from satellite altimetry as well as global tide gauges) is reflected in all the recently published global mean sea level reconstructions which include 19th century data.

The apparent reduction of decadal scale SLR in the 1960s and subsequent resumption of an increased rate of rise through the late 20th Century was for some time directly associated with a subjectively similar pattern of observed rate of change in global temperature at decadal and century scale as observed at the surface of the ocean and represented in high quality global datasets of both Sea Surface Temperature (SST) (Menne et al. 2018, Xu et al. 2021) as well as the surface of the entire planet (Kennedy et al. 2019, Morice et al. 2020). The changes in global sea level as observed by satellite altimetry since 1993 can be explained by summing the known contributions and sources of variability over this period (Cazenave et al. 2018), but until very recently it has proved difficult to reconcile SLR with known causes over longer timescales.

However, recent improvements in observational data (Tapley et al. 2019) and methods of analysis (Dangendorf et al. 2017, Zemp et al. 2019) have now allowed closure of the sea level budget since 1900 (Frederikse et al. 2020a) leading to a clearer understanding of the processes and uncertainties involved. The overall picture is more complex than a simple relationship of GMSL with temperature variation or monotonically rising CO_2 levels, although a linear sensitivity link between rate of SLR and temperature increase has been proposed (Grinsted & Christensen, 2021).

New studies on volume changes indicate that a significant contribution to the global SLR slowdown in the 1960s and 1970s was increased water impoundment in large scale dam projects (Hawley et al. 2020) through this period, unrelated to climate forcing. The impact of transient global cooling and reduction in upper ocean heat content due to large scale volcanic eruptions (Tokarska et al. 2019, Toohey et al. 2019, Stenchikov 2021) is also evident in the second half of the 20th Century (e.g. Pinatubo in 1991, Veng et al. 2020). In isolation, these factors will result in a global sea level deceleration component between 1950 and 1970, that will then become acceleration if the period is extended to 2020.

This suggests volcanic eruptions are also very likely to have played a role in sea level variation in the 19th Century (e.g. the large eruptions of Tambora in 1815 (Raible et al. 2016) and Krakatoa in 1883) given the relative size of eruptions and estimated scale of SO_2 release. Uncertainties remain in quantifying this release (Dhomse et al. 2020) as well as the resultant effect on global energy imbalance and steric sea level (Gregory et al. 2020). There are also large uncertainties in observations of glacier mass changes and temperature related volume changes before the 20th Century, although quality-controlled sea surface temperature records are available. In addition, observations of MSL become increasingly sparse going back into the 19th Century, and as discussed in part 2.2, some regions are particularly poorly represented. Nevertheless the sea level records that do exist from the mid 19th Century and earlier indicate a similar pattern of change from the 19th to the 20th century as observed in the global temperature record.

Superimposed on these global scale long term changes as recorded by tide gauges there is significant regional decadal and interannual scale variability. These fluctuations can bias trends derived from individual tide gauge records, and so understanding the causes can allow these effects to be isolated and accounted for.

2.6 Understanding the causes of temporal and spatial variation

2.6.1. Variability due to local weather

It has been known since at least the early 19th Century that sea level at any site varies with local wind conditions and atmospheric pressure (Daussy 1831, De la Beche 1839). By the second half of the 19th Century it was known that variations seen in tide gauge records from neighbouring stations were highly correlated at weekly or monthly and longer timescales, and that local weather conditions were responsible. Adjusting MSL data with a scaled version of local air pressure was successfully used to reduce this variability. Investigations of hourly resolution sea level, atmospheric pressure, and regional wind components (Doodson 1924, Ogura 1925) gave rise to a better understanding of this relationship in coastal waters following earlier work and empirical estimations (Daussy 1831, Lubbock 1837, Ross 1854, Ortt 1897, Close 1918). A large amount of shallow sea level variability can be explained using regression analysis of local and far field geostrophic wind data (or scaled North-South and East-West air pressure differences) (as shown for the UK by Thompson 1980), but for coastal shelf seas such as the waters around the UK this variability can be reduced yet further using barotropic tide and surge models (Woodworth et al. 1999, Cid et al. 2017; Piecuch et al. 2019; Hogarth et al. 2020) which also take bathymetry and the coastline into consideration. This last method is used in the case studies in this thesis, as described in chapters 3 and 4.

2.6.2. Far field effects

By the beginning of the 20th Century it was noted when comparing longer tide gauge records from stations up to a few hundred km apart that in many cases interannual variations in sea level were correlated (Thompson 1913, Marmer 1925). At several sites around the world this was linked to large scale variations in the atmosphere and ocean (Montgomery 1937, Jacobs 1939). At decadal time periods, correlation can still be seen between data from tide gauges hundreds or even thousands of km apart along Eastern and Western Ocean Boundaries (Enfield and Allen 1980, Papadopolous and Tsimplis 2006).

Douglas (1992) introduced the idea of coherence scale: tide gauge records show correlation at increasing spatial scales when the time series is lengthened. An example is the West Coast of the Americas, where interannual and decadal scale correlation is seen between tide gauge records from Canada all the way to South America. Coupled to this, analysis of both Altimetry based SSH since 1993 and tide gauge based coastal sea level observations over the past century or more shows a distinct see-saw pattern of sea level variation between Eastern and Western boundaries of the Pacific, both North and South of the Equator (Merrifield et al. 2012, Hamlington et al. 2015a, Royston et al. 2018). Considering the two longest tide gauge records in the Pacific, San Francisco in the US and Fort Denison, Sydney NSW, these are also at similar latitudes North and South, and are located on the Eastern and Western Pacific boundaries. It has been shown that the sea level recorded at each location, separated by almost 12,000km, appears to be modulated by opposing inter-annual variations (Hogarth 2014). These see-saw patterns are related to the complex thermodynamic effects associated with ENSO, and its atmospheric component, the Southern Oscillation Index (Bromirski et al. 2011, Merrifield et al. 2012). These ENSO and largely trade wind driven interannual sea level variations (Hamlington et al. 2020c) are large enough (excursions of several decimetre scale) to introduce relatively high levels of uncertainty to derived SLR and acceleration in regional satellite altimetry records (Hamlington et al. 2020a, Hamlington et al. 2020b), and at the ocean boundaries, can bias trends derived from multi-decadal tide gauge records (Hogarth 2014, Royston et al. 2018). Accounting for this kind of interannually recurrent pattern of variability observed in sea level records using climate indices independently derived from temperature or atmospheric datasets has been shown to reduce the timescale over which consistent trends can be derived. The apparent antiphase relationship across the largest ocean basin also suggests ways of similarly attenuating this variability at both locations. For example, a simple average of the long records from Sydney, New South Wales on the SW Pacific boundary and San Francisco, on the NE Pacific boundary cancels out much of the natural variability over a wide range of timescales seen in both records, which tends to be in antiphase due to tidal, seasonal and ENSO effects related to opposite but similar latitudes and opposite coasts of the Pacific. Although simplistic, the result is a much smoother representation of Pacific sea level.

The current understanding of these long distance teleconnections and the resultant regional coherence allows adjustment for far field ocean effects in regional mean sea level studies. One of these, using a common mode signal, is explored in the case study in chapter 4.

2.6.3 Application to UK waters

For the UK, these factors have been considered previously in sea level studies (Doodson 1924, Thompson 1980), and these and more recent work are discussed in more detail in Chapters 4 and 5. There are also known to be localised effects due to the shape of the coastline in relation to prevailing winds and bathymetry. These are the factors which a tide and surge model is shown to be particularly successful in accounting for, compared to a simple inverse barometer model. In terms of interannual variability there are both differences and similarities in tide gauge records from the East and West UK coastlines, as might be expected from the previous discussions, and there are further localised complexities. The area around the mouths of the Severn and Avon for example exhibits one of the largest tidal ranges in the world, and appears from levelling exercises and mean sea level measurements to show a water level gradient moving “uphill” towards the Severn. This may be a wind driven effect, but the quality of the local tide gauge records is poor and the land levelling across the estuary appears questionable. Across the Humber estuary, the land levelling shows a large step (see Chapter 5), and at a national scale, the difference in vertical land motion trends between Scotland (rising) and the South of England (subsiding) due to GIA is significant and results in differences in relative sea level trends. This becomes more problematic to disentangle when tide gauge datum shifts are present.

2.7 Summary.

At multidecadal timescales, changes in sea level due to impoundment of large volumes of water associated with dam building, the slow ocean response to intermittent transient events such as major volcanic eruptions, low frequency components of regional sea level variability due to variations in large scale ocean (Dangendorf et al. 2021) and atmospheric circulation patterns (Tinker et al. 2020) can all confound clear detection of any secular changes due to anthropogenic climate change. This variability can differ from region to region, so is likely to result in differences in derived regional trends unless accounted for, or unless records are long enough that the impact of these changes and fluctuations is minimised.

To extract trends with minimum uncertainty then adjustment for the various sources of variability is necessary (as far as is possible) coupled with use of the longest regional time series available (by extending these series wherever possible, Fig. 2.7).

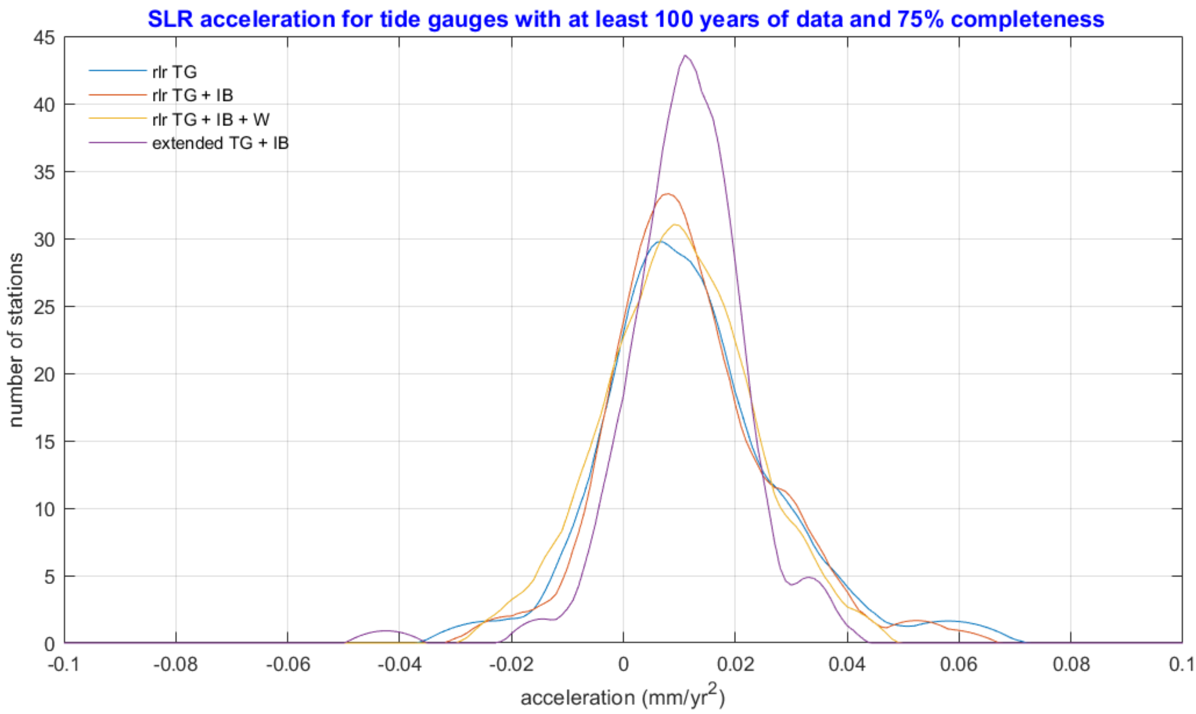


Figure 2.7: Probability density functions showing the increased homogeneity in second order trends gained from adjusting and extending the number of global tide gauge time series (here 115 sites as opposed to 71 RLR PSMSL sites with >100 yrs and >75% completeness), updated from Hogarth (2014). Blue is the unadjusted RLR time series, red includes

adjustment for Inverse Barometer using linear regression, showing little change to the spread of trend values, the yellow PDF includes the additional effect of geostrophic winds, again showing little effect on the trends for century scale records. The purple pdf shows the reduction in spread of trend values as a result of extending the time series where possible and increasing the number of sites.

Chapters 4 and 5 of this thesis act as case studies dealing with these two aspects of sea level time series analysis, based on regional data limited to the coastline of Great Britain.

Chapter 3: Processing MSL data: Problems and solutions

This chapter describes in more detail some technical issues related to datum shifts covered only briefly in the papers (chapters 4 and 5), giving some background account of the evolution of the research and solutions. In the UK case study in chapter 4 a main finding is that datum shifts exist even in monthly MSL data which has been quality controlled, and these offsets can cause cm scale differences between records from nearby tide gauges, which can result in errors in derived SLR trends. Unless measures are taken to reduce other confounding sources of variability, these datum shifts can escape scrutiny and remain challenging to detect and account for if the amplitude is small relative to other components of sea level variability. Examples of other sources are those due to meteorological effects (covered in section 3.4) or vertical land movement such as GIA over time (covered in section 3.3), which may appear as a datum shift if tide gauge levelling observation frequency is low. Even a single datum step can be misinterpreted as local low frequency variability using standard spectral analysis techniques (this is explored using simulated steps and model data in section 3.2). Section 3.1 explores the various causes of datum shifts in tide gauge data.

3.1 Datum changes

3.1.1 Changes in instrumentation

Land based reference points which have been stable (or precise knowledge of how these reference points have changed over the measurement period) are essential for analysing changes in sea level as measured by land based tide gauges. The zero point of the tide gauge measurement system will usually be set and levelled at a fixed recorded elevation relative to land based bench marks, linked to a national levelling datum, such as Ordnance Datum Newlyn (ODN) in the UK. If the instrumentation changes, for example if the tide gauge is renewed or relocated, then the zero point needs to be re-levelled to the same bench marks with mm scale precision to maintain continuity of the sea level record. As will be demonstrated in Chapter 4, too often these changes are either not recorded, or are not measured consistently. In addition, tide gauges must be regularly calibrated (simple but precise calibration methods have been available and used since the 19^{th} Century, see Chapter 2, 2.1.2). Periodic re-levelling of the tide gauge reference point also allows any structural subsidence to be identified at an early stage. Again, all too frequently, there are periods when gauges were poorly maintained or not calibrated, and multi-cm scale errors can be introduced into the tide gauge records. If not accounted for then errors at individual sites can be large, and derived SLR trends can be entirely misleading (see Chapter 4). Historically, where data from a site is judged to be high quality, datum shifts in records from nearby sites have been identified by comparing with the reference site, or differencing the time series record (a process sometimes called "buddy checking", see Pugh and Woodworth 2014), however unless more than one comparison site is used, the results can be ambiguous.

Chapter 4 also shows how existing metadata, even if sparse, can be used in combination with buddy checking to estimate unrecorded datum changes and reduce these errors by an order of magnitude. It will be shown that this is a significant step forward in terms of quality control of tide gauge data.

3.1.2 Accounting for step-like differences between MSL and MTL

Another potential source of error is changes in the way results are recorded (such as sampling frequency). For example self-recording tide gauges produce a continuous record of the changing tide, so that deriving MSL is straightforward, if time consuming. However tidal ledgers maintained by many harbour-masters usually recorded only daily or twice daily high and low waters, as described in Chapter 1. At many sites only these HW and LW records are available for some periods of otherwise continuous long MSL records (e.g. Aberdeen, Cuxhaven, and Fort Denison, Sydney), and thus whilst MTL is easily computed, MSL cannot be derived directly, and must be estimated from the relatively stable but site specific relationship between MSL and MTL (Bruyn 1900, Marmer 1932). In some cases this difference can amount to cm scale, and will appear in the unadjusted record as a level or datum shift, which can be difficult to untangle from the cm scale interannual variability typically seen in tide gauge records.

For example the century scale record from Mumbai contains a section of MTL from 1931 to 1958 whilst the earlier and later sections are MSL. If differences between MTL and MSL are not accounted for, then the overall record shows no statistically significant acceleration. Following MTL to MSL adjustment of -32 mm for the section of MTL derived from analysis of available high frequency records, the record shows long term acceleration of similar magnitude to that found in other long records. Unfortunately, despite this factor being previously estimated and accounted for in the early 1960s (Chugh 1961) the unadjusted record was later used in several well cited regional and global studies leading to analytical errors. Following discussions with P. Woodworth and the PSMSL initiated by previous investigations relating to the PSMSL record from Mumbai (Hogarth 2014), the PSMSL added an MTL flag for all affected sites in their database to alert users to this factor, and this topic has now been comprehensively covered by Woodworth (2017) who gives estimates of adjustments for many sites.

3.1.3 Changes due to engineering works altering the tidal regime

Changes in tidal range at any site can have multiple causes (Haigh et al. 2020, Jänicke et al. 2020). A difficult challenge when assessing historical records from coastal tide gauges is dealing with changes in tidal regime due to civil engineering works such as deepening of navigational channels by dredging or reef removal. Often these changes were substantial, (Talke and Jay 2020) and occurred over periods of time.

For example at Leith Harbour, the sill of the dock was said to be 2 to 3 feet (around 600 to 900mm) under low water in 1826, but after clearing and deepening of the channel approaching the harbour over the next ten years the sill was frequently dry at low water (it is also stated that during the previous century that the depth of the bar had remained without alteration) (Walker 1835). Similar accounts widely spaced over the 19th and early 20th Century strongly suggest that the tidal range (specifically the lowering of low water levels towards that of the adjacent open sea) in many ports and harbours at or some distance from the mouths of rivers increased due to measures designed to allow ever larger vessels into the docks. An example is dredging of the naturally occurring sand bars which used to restrict access at low water to many of the major ports in Europe. One effect of this change in range, which is sometimes preserved in tidal records, is to lower observed MTL over this period, as HW levels were much less affected by increased channel depths. Almost by definition, affected sites were in shallow water, and changes in depth also affect the proportions of higher order harmonics in the tidal cycle, on which the assumed constant relationship between MTL and MSL depends (see 3.1.2 above). This means that some caution is required when interpreting old tidal records from affected sites. In the case of Leith, the available early tidal records (1827 to 1840) are of HW only (Whewell 1842), so we cannot directly quantify changes in MTL. In some cases, as at Liverpool and North Shields, we have historical records from several stages from the river mouths upstream measured at different periods, which clearly show significant changes in low water levels as alterations were made. These observations, although often recorded over relatively short periods, can allow such changes to be estimated. If these changes are not accounted for, then any elevated MTL levels recorded before these works were carried out, (often around the mid 19th Century in the UK) could potentially lead to artificially higher long term sea level acceleration estimates. As sites which have data from this early period are few, and inter-site comparisons are difficult, this becomes an important consideration when extending tide gauge time series.

3.1.4 Baseline changes due to Seismic activity.

A further issue of datum stability arises when considering sites which have been affected by seismic activity during the period of recording, such as those in Alaska, many sites in Japan, and some island sites such as Port Blair. Often such earthquake induced vertical land movements are recorded clearly on the tide gauge records, but accounting for these datum steps in historical records is not straightforward as changes are rarely as simple as an instantaneous offset step (Klos et al. 2019). As we focus here on the coastline of the UK, which is relatively stable seismically, we will defer this interesting problem to future work.

3.2 Simulating datum steps

3.2.1 quantifying the effect of datum steps

To quantify the potential impact of datum or mean level steps (from whatever source) on estimates of sea level trend, an idealised step free analogue of typical tide gauge data was created by using surge model data for a selected UK site (as this closely simulates the noise spectrum of real data) and adding a linear trend. The model used here, CS3X, is discussed in more detail later in chapter 4. First the effect of the added variability on the known trend was estimated. Then a fixed amplitude step function was added to the model data series, and then trends were derived for a large number of iterations over randomised step positions. The CATS processing method was used for trend and uncertainty estimations (Williams 2008). Any number of steps of either polarity could be added and similarly modelled. A probability density function of the resultant trends gives statistical information on the impact of such steps on ideal data. This showed that a large percentage of the spread in SLR trend values for UK tidal stations could potentially be explained by random datum steps with amplitudes similar to the ones seen in real data. For example a single 50 mm offset in a 60 year time series with identical MSL variability to Newlyn can on average increase the spectral index by around -0.6 and alter the SLR trend by 0.6 mm/yr. The presence of undetected steps may partly explain why some tide gauge data exhibits higher spectral indices (Bos et al. 2013) and trend differences from those of nearby sites.

It then seemed reasonable to test various step detection and correction methods on the model data, for which the step amplitude, position in time, and initial trend are known (Fig. 3.1).

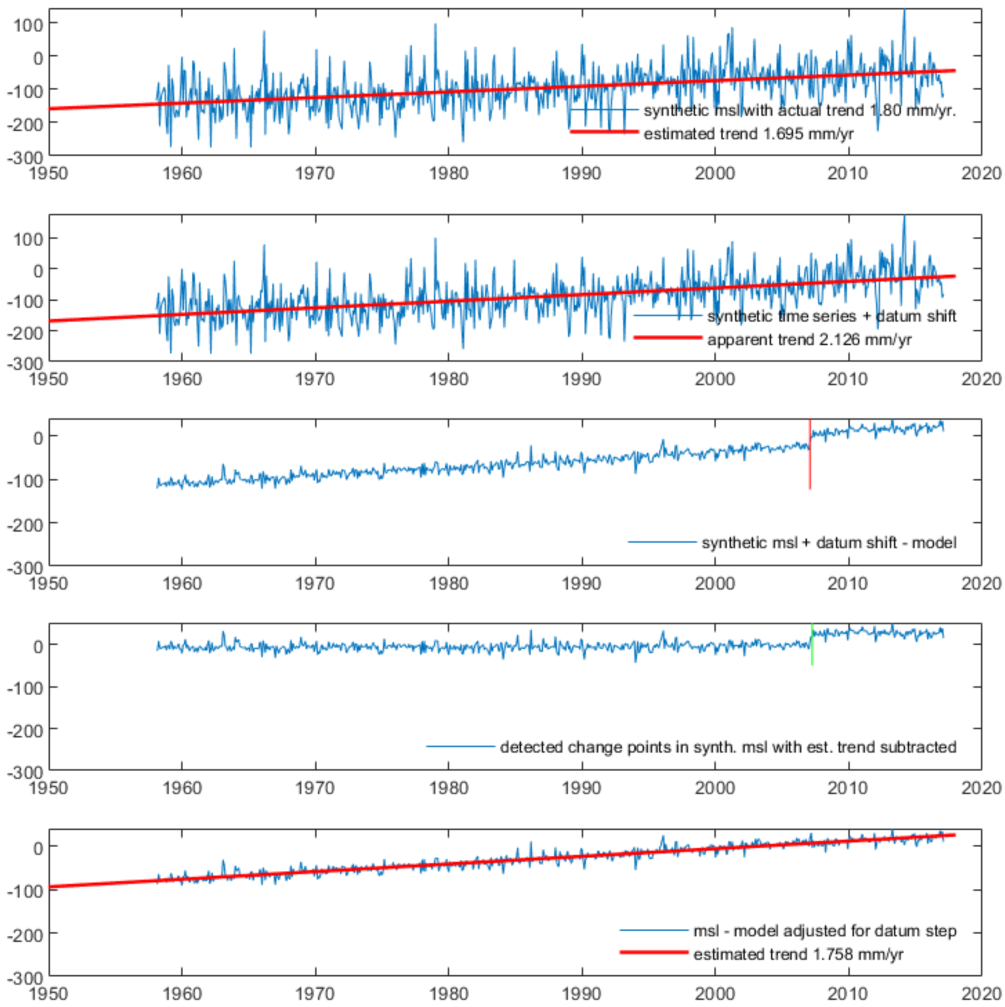


Figure 3.1: (a), synthesised MSL for Newlyn site with added trend of 1.8mm/yr, showing derived trend with approx. 0.1mm/yr error due to influence of variability. (b), synthesised MSL for Newlyn site, with 25 mm upward step introduced, and apparent trend showing error of + 0.33mm/yr. (c), synthesised Newlyn record with step minus synthesised MSL from Devonport, with step position marked (red). (d), de-trended record with step position estimated from auto-change-point detection process. (e), reconstructed MSL with estimated step correction subtracted, and derived trend.

In addition, it could be shown that the power spectrum of the difference between two nearby modelled sites (Fig. 3.2) was flat, i.e. differencing two nearby step free time series effectively removed variability in the residual over a very wide range of frequencies. It could be further shown that the effect of adding a step function to one of the time series introduced variability in the difference over a broad range of frequencies, with a power spectrum showing a power law response. A single offset step (or sequence of step functions) has a relatively smooth spectral slope of spectral index -2.0, identical to that of random walk noise (Fig. 3.2).

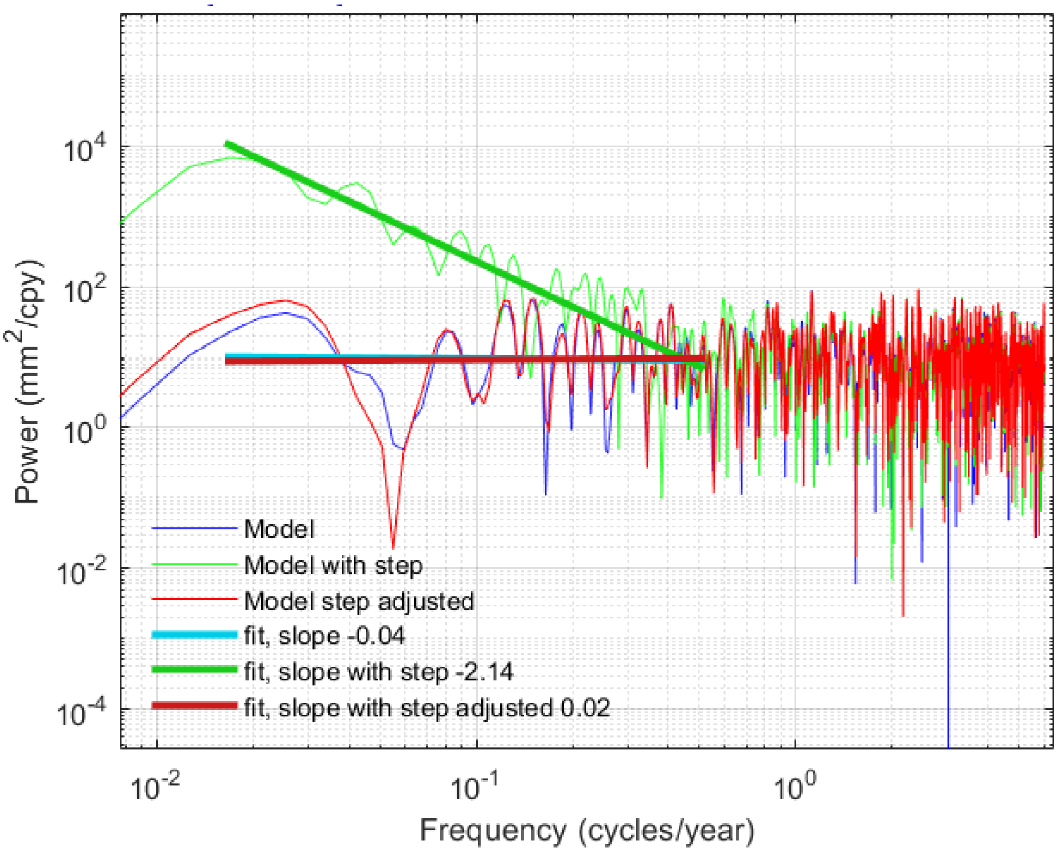


Figure 3.2: blue: power spectrum of difference of simulated time series from nearby tide gauge sites (Newlyn and Devonport), green: time series of same difference with 50mm step added to Newlyn), and same time series with auto-adjustment of step (red).

An auto-detection and adjustment method developed using the MATLAB maximum likelihood change detect function was then applied to observed monthly MSL data for UK sites, and appeared to give realistic adjusted trend estimates for sites such as Workington, where a series of clear downward datum steps results in an apparent negative sea level trend in the unadjusted data (see Chapter 4), and for sites such as Tilbury where multiple datum changes between ODN and elevations of order -3 m ODN were present in the unadjusted Metric data. Predictably however, this method failed where the data appeared to show gentle slope changes (for example Portsmouth in the 1970s) and proved sensitive to time estimate errors caused by the residual short-term amplitude variability superimposed on interannual or lower frequency components (i.e. local gradient changes or any low order changes such as decadal scale acceleration/deceleration). As this low frequency variability is intrinsic to MSL time series, application of this type of analysis was judged to be limited.

3.2.1. Datum steps as low frequency error source

In chapter 4, we present a case study outlining a quality control method of processing monthly MSL tide gauge records involving a sequence of adjustments aimed at reducing the effects of 1) unresolved datum errors, 2) meteorological variability and 3) far field ocean effects. To investigate the effect of each processing step at different frequencies, we used the Lomb-Scargle estimate of power spectral density available in MATLAB, which allows missing samples (Lomb 1976, Scargle 1982, Press and Rybicki, 1989). Results for time series from individual sites associated with large datum offsets displayed relatively more energy at low frequencies, and an increased spectral index (SI), here defined as the slope of a least squares fit to the power spectrum over periods greater than two years (with a practical lower cut-off of around half the record length). This was tested, showing a single cm scale step in a simulated sea level time series can significantly redden the spectrum. This increase of spectral power at lower frequencies (coloured noise) will increase estimated uncertainties in trend (Bos et al. 2013).

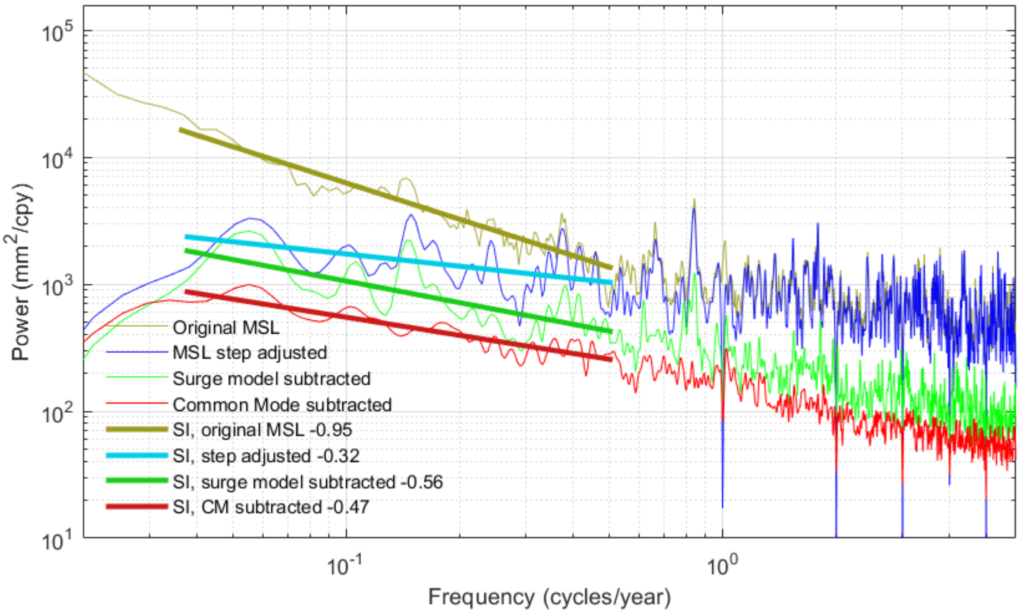


Figure 3.3: Average of power spectra for sites around the British Isles, summarising the frequency related impact of the various adjustments described in this paper. Adjusting for datum steps greatly reduces low frequency variability, which will tend to have a greater impact on trend analysis. The tidal surge model has greater impact at higher frequencies where variability is driven predominantly by meteorological effects. The common mode

signal affects a broad range including lower frequencies. SI (Spectral Index) is the slope of the curve on a log-log plot, and can be used as an indicator of coloured noise, a higher index means higher energy at low frequency.

Fig. 3.3 summarises the results for the averaged spectra from all sites, and shows that removing datum steps removes a large amount of spectral power at lower frequencies, and this is likely to impact trends as well as uncertainties at individual stations as shown by the case studies in Chapter 4.

Several methods of step detection have previously been tried with environmental time series data. Maximum likelihood change functions initially appeared well suited to "blind" step detection and quantification of tide gauge records. The use of the maximum likelihood change detect function in MATLAB needs care in this application. Any localised gradient in the time series can be misinterpreted as a step due to the gradual change in mean value. Therefore we use the function in a two-part process. In order to prevent the detrending process being itself biased by the presence of steps, the maximum likelihood changepoint detection function in MATLAB is used first to divide the deseasonalised monthly MSL time series into segments based on changes in slope. A weighted mean of robust estimates of the local segment slopes is then derived for the whole series. This initial estimate of mean trend was then removed from the original data to optimally detrend the series, and then a new changepoint detection process was run based on mean level differences and a minimum threshold (at mm level). No initial assumptions were made about sea level rise (i.e. this was initially assumed to be zero).

Tests based on introducing a step into an artificially generated step free model time series with the correct spectral character show that this method reduces the mean SLR trend error by approximately an order of magnitude (from around 0.5 mm/yr to less than 0.05 mm/yr) for a 30mm step anywhere in a 60 year modelled monthly MSL time series (Fig 3.1). This remaining insignificant trend error is comparable with that introduced by meteorological variability over the same period in this region (for Newlyn this is approximately -0.1 mm yr^{-1}). However, application to real records proved challenging in several cases, and as outlined in Chapter 4, a more robust method was developed which used the change detect function only as an additional check.

3.3 Regional trend variability: accounting for first order effects due to GIA

Estimating a global or regional average SLR value is problematic for several reasons. Assuming a global climate related SLR signal can be separated from other sources of variability, the nature of the tide gauge database means that some coastlines are better represented than others in terms of site density, quality, and length of record. Some coastlines, such as the Baltic, are strongly affected by ongoing post glacial rebound, and the long term relative sea level can appear to be falling in the Northern Baltic, and rising slowly or not at all as we examine tide gauge sites further South towards the North Sea. As we have seen in Chapter 1, some of the longest sea level time series in the world are from the Baltic region. In order to estimate an average sea level index for the Baltic for example, so that this can contribute to a global average, then the influence of differing vertical land motion must be accounted for in order to normalise the trends first. Historically this was done for regional sites by using one record as a reference and then differencing each site record from this reference to obtain relative trend differences. Using long term sea level trend differences to estimate post glacial rebound has a long history (Gutenberg 1933, 1941, Jolly 1939, Valentin 1953, Edge 1959). Whilst locally there may be sediment compaction or, occasionally, physical bench mark displacements which can cause differences in apparent VLM, several tide gauge based levelling studies over many decades in the UK, Ireland, USA (Avers 1927) and Australia have in the past revealed an apparent systematic variation in RSL trend value with latitude (Leypoldt 1937) which could alternatively be interpreted as a long term slope in regional sea level change. It is now known that these apparent slopes are mainly due to systematic errors in the historical land levelling campaigns. These errors are largely resolved using modern Geodetic techniques, based mainly on geocentric CGPS measurements, combined with other precise space based measurement systems such as the French satellite system Détermination d'Orbite et Radiopositionnement Intégré par Satellite, or in English, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and satellite laser ranging (SLR). These are all used in establishing and maintaining a Geocentric reference frame, known as the *International Terrestrial Reference Frame* (ITRF), ITRF2014 being the latest iteration, although ITRF2008 is the version currently used in satellite altimetry and GNSS (Altamimi et al. 2011). The orientation of this reference frame (and thus the Earth's orientation and rotational and orbital motion) is itself referenced to an inertial reference frame using Very Long Baseline Interferometry (VLBI) which uses large numbers of time difference measurements from many distant quasars observed with a global network of radio antennas.

A more systematic and globally consistent way of dealing with differing rates of vertical land motion (VLM) at tide gauge sites is thus to estimate the geocentric vertical land motion (assuming the VLM rate is constant at century scale) and remove this as well as any gravity related geoid (Bruns 1878, Siegismund et al. 2020) component directly from the RSL trend. Geocentric SLR trends have been derived from tide gauge data using several methods.

1. GIA models (constrained by GNSS measurements)
2. Tide gauge and satellite altimetry time series difference trends
3. Direct VLM measurement using GNSS receivers based at the tide gauge
4. Intercomparison of long term tide gauge records where GNSS is not available with a record from a nearby site which has been adjusted using method 3 above.

N.B. methods 2 and 3 only give vertical land movement, and do not account for geoid variations.

Studies of global SLR based on satellite altimetry are independent of vertical land motion at the coast, but still use SSH data adjusted for the relatively small effect of GIA at the ocean floor, estimated to be -0.3mm/yr, (Peltier 2006) or -0.13 mm/yr (Vishwakarma et al. 2020) when observed ocean mass changes are accounted for. All older altimetry data sets have now been updated (Topex/Poseidon and ERS) and are now processed to a uniform geocentric reference frame, ITRF2008.

For the UK, the pattern of relative vertical land motion (assuming a uniform mean sea level around the coast) derived from the two main OS levelling campaigns follows a similar pattern to the modelled and GNSS measured relative geocentric downward crustal movement in the south of England and upward motion in Scotland (Rennie and Hansom 2011, Shennan et al. 2012).

3.4 Regional trend variability: accounting for meteorological effects

In Chapter 1: 1.5.1 we reviewed how sea level measurements were adjusted for local weather, particularly air pressure, and how current best practice involves the use of barotropic models (at least for shallow continental shelf seas such as those around the UK and Ireland). This is the approach used in Chapter 4. It was also noted that such models do not generally cover the 19th Century. To allow adjustment for this period the best currently available meteorological data was needed. Initially, the meteorological reanalysis data used was: ERA Interim, with data from 1978 onwards (Dee et al. 2011), coupled with long term reconstructed data sets, e.g. ERA-20C from 1900 (Poli et al. 2016), and HAD-SLP2 from 1850 (Allan & Ansell 2006) as well as regional historical reconstructions (e.g. Luterbacher et al. 2002 with European SLP data from the 18th Century onwards) for data prior to 1850.

Later in the research project, two improved reanalysis products became available: ERA5 (initially covering 1979 to now, and then extended back to 1950 as from March 2021) and 20CRv3 (covering 1836 to 2015) (Slivinski et al. 2019). The tide gauge analyses in this thesis use composite meteorological data from these updated sources. Older and recent literature on intercomparison of SLP data sets and IB correction had already been reviewed (e.g. Compo et al. 2014, Piecuch et al. 2016). The available data sets were compared, and full time series of best estimates of monthly mean SLP at each tide gauge site were produced using simple regression based on Least Squares Analysis (LSA) in overlapping time periods, accounting for known anomalies. These were then further quality checked site by site.

Estimated SLP mean offset or standard deviation changes at transitions between the different reanalyses used to create the composite meteorological time series at each site are reduced to mm (sea level equivalent) level, which minimises impact on SLR trends when used for IB adjustments. Monthly zonal (conventionally U is positive flow from West to East) and meridional (V is positive flow from South to North) wind components are also used from the same reanalyses to calibrate pressure difference derived wind components estimated from the overlapping gridded historical SLP data. This allows creation of continuous U and V wind time series for the region around each tide gauge site prior to 1836, as the historical data only gives SLP and not U and V directly prior to 1836.

The next step, discussed in Chapter 4, was to use the barotropic model described in Chapter 4 regressed with the extended composite pressure and wind time series for each site. The existing and extended monthly tide gauge time series described in Chapter 4 have been adjusted using this new statistical model. Many of the long continuous time series available in the PSMSL showed a visible reduction of monthly variability extending back well into the 19th Century (figure 3.4), suggesting any short section of MSL data (such as a few weeks or months record) could also be adjusted.

Note that we use the reanalysis pressures to make an IB correction, then regress the IB corrected surge model predictions (not the tide gauge data) on reanalysis pressure gradients. This ensures that the regression only mimics barotropic ocean processes driven by local winds, and does not absorb any sea level signal due to more distant winds, which may be correlated with local winds. We found this to improve results in the period not covered by the storm surge model.

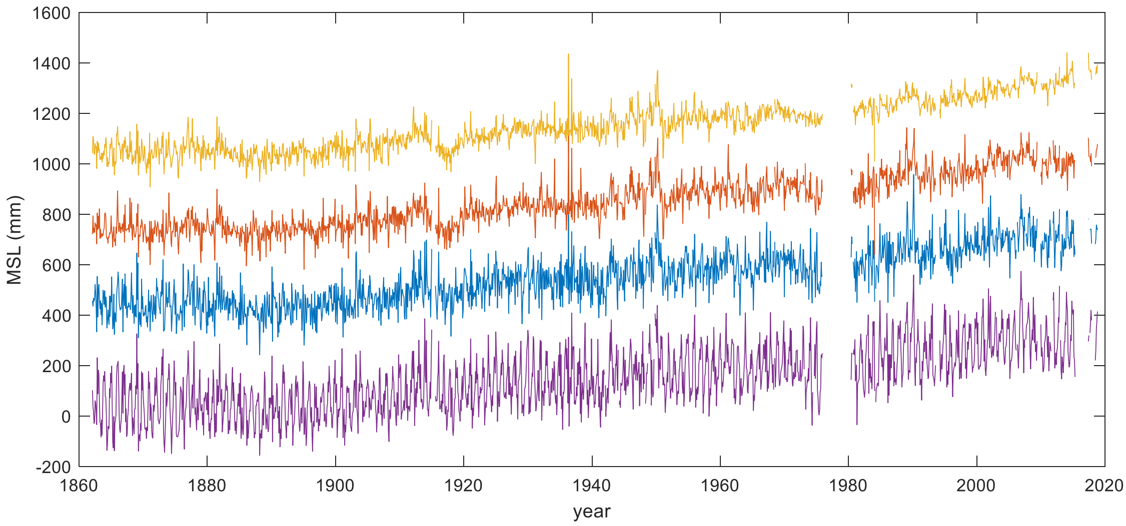


Figure 3.4: Purple (bottom curve) is monthly MSL composite time series for Aberdeen adjusted for GIA and known RLR and datum offsets. Blue (second curve up) is further adjusted for seasonal components. Red (third curve up) has also been adjusted for IB (inverse barometer) to account for meteorological effects. Orange (top) is as the blue curve, but has been adjusted for meteorological effects using a barotropic tide and surge model which has been regressed using interpolated SLP and U and V wind components from 20CRv3. This visibly reduces seasonal and meteorological variability. Curves are vertically offset for clarity

3.5 summary

In Chapter 2 we have discussed some of the methods tried and used to adjust for various sources of variations in linear RSL trends, and interannual variability in MSL records, as well as errors in baseline (datum) continuity. In the chapter 4 we present the results of applying these adjustments to all of the available tide gauge records around the UK coastline with at least 20 years of data, where looking at and comparing results from many sites allowed development of an optimised overall methodology.

Chapter 4: Case study: MSL for the waters around the British Isles since 1958

Context of the paper in relation to the thesis

This paper, which forms chapter 4, addresses the first main research aim of the thesis given in the introduction, by investigating optimal methods of removing the influence of non-climate related variability in tide gauge MSL records. During this investigation, it was realised that (in addition to predicted meteorological and far field ocean effects), datum errors were a significant and unforeseen source of low frequency variability, even in records which had previously been quality controlled. The important step of removing known sources of variability now made these errors much more easily detectable. Different methodologies were investigated in order to automatically correct these datum errors in actual records, resulting in the systematic method presented here. One effect of these errors was to introduce non-sea level related differences between records from relatively close sites. One of the main findings of this paper was to show that once the datum errors have been removed as far as possible, that records followed a similar pattern of variability to a UK wide common mode or average annual sea level curve, which was found to be strongly linked to the variability along the entire north-eastern Atlantic boundary.

This work has been published as: Hogarth, P., Hughes, C. W., Williams, S. D. P., & Wilson, C. (2020). Improved and extended tide gauge records for the British Isles leading to more consistent estimates of sea level rise and acceleration since 1958. *Progress in Oceanography* **184**, 102333. https://doi.org/10.1016/j.pocean.2020.102333.

As lead author I led the research, compiled, digitised, checked and interpreted the data, wrote the paper, generated the MATLAB code, plots and tables and managed the publication process. My supervisors Chris Hughes and Simon Williams provided valuable supervision, and suggestions for efficient analysis methods. Simon Williams provided CS3X model data at tide gauge sites. Chris Wilson ran the CS3X model and provided a description. All co-authors provided editorial critique, and discussion of ideas.

Permission to include this paper in the thesis is given by all three co-authors:

Chris W. Hughes:

Simon D. P. Williams:

Chris Wilson:

C. Wilson

“Improved and extended tide gauge records for the British Isles leading to more consistent estimates of sea level rise and acceleration since 1958”.

Hogarth, P.[1,2], Hughes, C. W.[1,2], Williams, S. D. P.[1], Wilson, C.[1], ([1,] National Oceanography Centre, Liverpool, L3 5DA, United Kingdom, [2,] University of Liverpool.)

Corresponding author: Peter Hogarth (pehoga@noc.ac.uk)

Peter Hogarth, Floor 1, NOC, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA

Key words: sea level rise; sea level acceleration; mean sea level; tide gauge; time series analysis

Abstract

This paper describes methods of obtaining improved estimates of long-term sea level trends for the British Isles. This is achieved by lengthening the sea level records where possible, then removing known sources of variability, and then further adjusting for datum errors that are revealed by the previous processes after verification using metadata from archived sources. Local sea level variability is accounted for using a tide and surge model. Far field variability is accounted for using a "common mode". This combination reduces the residual variability seen at tide gauges around the coast of the British Isles to the point that a number of previously unrecognised steps in individual records become apparent, permitting a higher level of quality control to be applied. A comprehensive data archaeology exercise was carried out which showed that these step-like errors are mostly coincident with recorded site-specific changes in instrumentation, and that in many cases the periodic tide gauge calibration records can be used to quantify these steps. A smaller number of steps are confirmed by "buddy-checking" against neighbouring tide gauges. After accounting for the observed steps, using levelling information where possible and an empirical fit otherwise, the records become significantly more consistent. The steps are not found to make a large difference to the trend and acceleration observed in UK sea level overall, but their correction results in much more consistent estimates of first order (Sea Level Rise) and second order (Sea Level Acceleration) trends over this 60-year period. We find a mean rate of sea level rise of 2.39±0.27 mm yr^{-1}, and an acceleration of 0.058±0.030

mm yr^{-2} between Jan. 1958 and Dec. 2018. The cleaner dataset also permits us to show more clearly that the variability other than that derived from local meteorology is indeed consistent around the UK, and relates to sea level changes along the eastern boundary of the North Atlantic.

4.1. Introduction:

Our overall aim in this paper is to extend and improve the British Isles monthly Mean Sea Level (MSL) dataset, to begin to understand the sources of the observed variability in the improved dataset, and to quantify sea level trends and accelerations.

This paper significantly improves the sea level records: (1) by using results of a data archaeology exercise to extend the sea level data set where possible; (2) by making use of a barotropic model to remove much of the variability due to local meteorology; (3) by deriving and subtracting a common mode, representing variability from more distant sources. This results in much smoother residual data, in which steps due to data recording errors are more apparent, leading to (4) a further data archaeology exercise demonstrating that most of those steps are associated with known instrumentation changes, and that levelling and related data are available for most segments of data between steps, allowing them to be objectively adjusted. We also (5) adjust those segments for which such information is not available, so as to minimise the steps. Finally (6) it is shown that the resulting dataset is more consistent and results in improved estimates of trends and accelerations of sea level rise around the British Isles. We have selected a minimum of 20 years of valid data to derive SLR trends, and 50 years to derive acceleration.

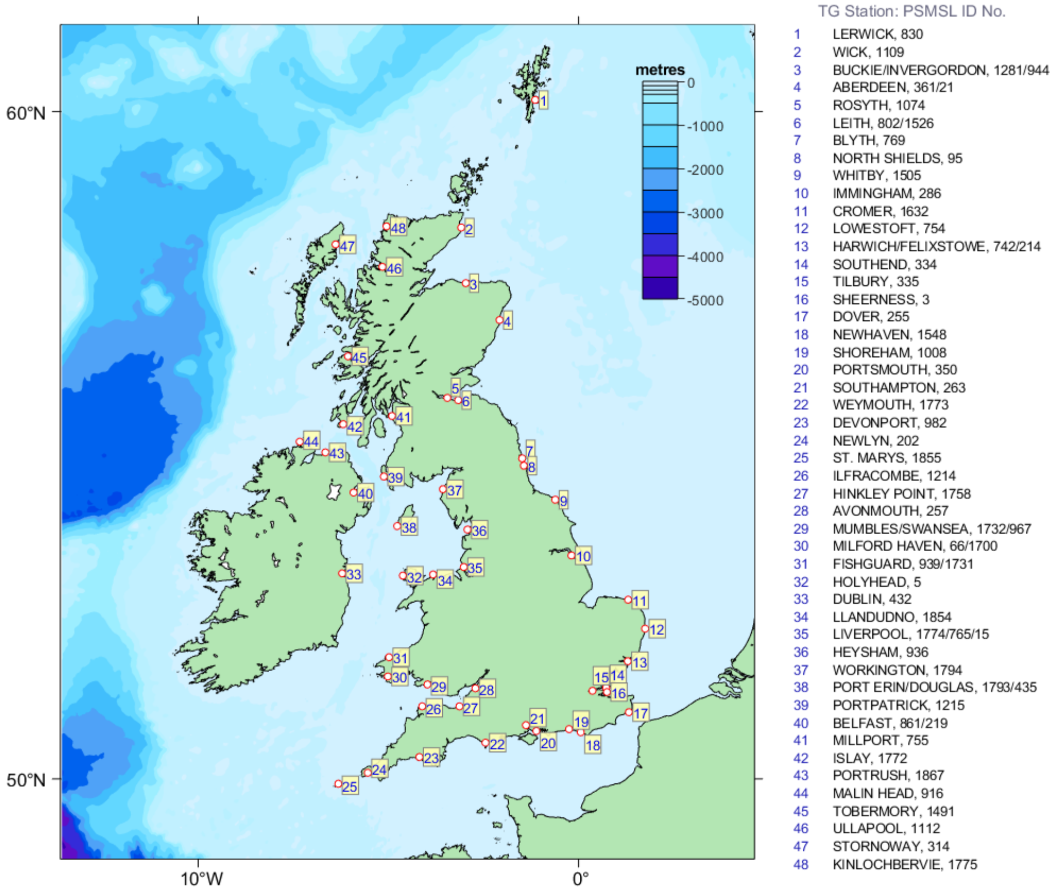


Figure 4.1: Tide gauge stations around the British Isles with more than 20 years of data, indexed starting at the northernmost station in Shetland, then clockwise around the coastline, with station name and PSMSL station number (or numbers if composite). Sites will use the index numbers (in parentheses) throughout this paper to ease reference.

The tide gauge network (Fig. 4.1) around the British Isles is a dense series of coastal sea level measurement sites situated on a shallow continental shelf sea on the Eastern boundary of the North Atlantic. The data from tide gauges installed around the British Isles and along the adjacent continental coast have been the subject of scientific study from the early 19th Century. More recent work has investigated sources of variability, allowing more refined estimates of Sea Level Rise (SLR) in the region (Rossiter 1967; Thompson 1980; Woodworth 1987; Woodworth et al. 1999; 2009a; Wahl et al. 2013; Dangendorf et al. 2014; Haigh et al. 2009; 2014; Frederikse et al. 2016a; 2018). This paper can be viewed as part of this ongoing process.

The Permanent Service for Mean Sea Level (PSMSL) is the main repository for global tide gauge data (Holgate et al. 2013). The 'Metric' MSL dataset contains monthly means of the original data for each site and is usually referenced to the tide gauge zero (TGZ) that was used at the time of recording (further background is given in Supplement 4.1). The Metric data therefore normally retains all the original (often large) TGZ changes, reflecting events such as gauge relocation or replacement, or redefinition of local Admiralty Chart Datum (ACD) (Aarup et al. 2006). The Revised Local Reference (RLR) dataset represents quality-controlled monthly mean data where records of these changes allow correction (as far as possible) to a consistent local land-based vertical reference point. Whilst the records have been subject to review, comparison and quality control over many decades (Graff and Karunaratne 1980; Woodworth 1991), a portion of the Metric data has not been reduced to RLR as the elevation differences between the TGZ and local bench marks were unknown or uncertain. In order to maximise the amount of useable data we initially carried out a data archaeology exercise (see Chapter4: 4.3) which allowed the recovery of new (as well as verification of existing) information, increasing the number of sites around the British Isles where RLR type offsets can be applied. The degree of this data extension is summarised in Fig. S5 in supplement 4.1. In all, the PSMSL holds monthly MSL data of varying record length and quality for around 100 sites around the British Isles. By including the newly extended and composite records, we increase the number of sites which have 20 or more years of data over the period from the late 1950s to the end of 2018 from 34 to 48.

The tide gauge measurements around the coast of the British Isles are affected by a range of different physical processes. These include: responses to local atmospheric pressure (Doodson 1924; Ponte 2006); wind stress (Thompson 1980; 1981) including tide and storm surges (Frederikse et al. 2016a; 2018); a response to more distant ocean variability (Wakelin et al. 2003; Calafat et al. 2012; Frederikse et al. 2016b; Volkov et al. 2019) which modulates and includes global mean sea level changes; local vertical land motion (VLM) (Wöppelmann et al. 2016) due to present day processes (such as localised subsidence due to groundwater extraction, or potentially for North East England, coal mining) (Rossiter and Gray 1972); and both land and gravitational responses to past glaciations, known as Glacial Isostatic Adjustment (GIA) (Bradley et al. 2011). Of these, the meteorological response and GIA response are expected to vary substantially, while the response to more distant ocean variability is expected to be more consistent from gauge to gauge. In Chapter 4: 4.4.3 and 4.5.3 we exploit this understanding.

In chapter 4, 4.2 describes the data sources, and 4.3 describes the data archaeology (more detail on the kinds of data sources and details of tide gauge datum determination are given in supplements 4.1, 4.2 and 4.3). In Chapter 4 parts 4.4 and 4.5 we work through the data improvements, using two example tide gauge sites in part 4.4, and then the entire dataset in part 4.5. These improvements take the following form:

- Step 1 (chapter 4: parts 4.4.1 and 4.5.1): Add levelling information to Metric and newly found data to produce the extended, RLR-quality Metric Extended Reduced dataset, with no further datum correction at this stage. Even for sites where no new data has been added, the recovery of levelling and tide gauge zero elevation metadata can allow resolution of large datum differences between sections of Metric data so that they now exhibit a degree of datum continuity more suitable for trend analysis. This effectively extends the useable time series.
- Step 2 (Chapter 4: parts 4.4.2 and 4.5.2): Perform "buddy checking" against nearby tide gauges, where possible, to demonstrate that previously undetected datum steps are visible, and make an estimate of their times.
- Step 3 (Chapter 4: parts 4.4.3 and 4.5.3): Minimise variability to make datum steps more visible. This is done by a) subtracting variability due to modelled GIA and the response to local meteorology from a barotropic ocean model, to make the time series at different sites more strongly correlated, b) creating a detrended Initial Common Mode, as an average of all tide gauge time series from a), each quadratically detrended. c) subtracting this Initial Common Mode from each detrended tide gauge, to make a time series in which datum steps are more clearly detectable.
- Step 4 (Chapter 4: parts 4.4.4 and 4.5.4): Identify "events", defined as times at which steps are likely to occur due to tide gauge changes (each event must be confirmed by a coincidence of an observed step and, usually, the time of a documented tide gauge change or, occasionally, a step identified from buddy checking with two other tide gauge records).
- Step 5 (Chapter 4: parts 4.4.5 and 4.5.5): Apply vertical offsets to segments of records between events. These offsets are in most cases derived from independent datum information. Where this is not available ("free-floating" segments), steps are estimated by minimising the difference from the quadratic trend derived from the constrained data.

Chapter 4: parts 4.4.6 validates the adjustment procedure for “free-floating” segments, by comparing different methods, and the end of section 4.5 describes the changes which have been made by all these datum corrections.

Chapter 4: part 4.6.1 discusses the variability in the resulting improved, detrended time series, and part 4.6.2 shows that, when the trends are retained, the new data now shows much more consistent linear trends. In part 4.6.3 we introduce the Final Common Mode – an average of all tide gauge sites after removing variability and datum steps – and show that the scatter of trends relative to this average is substantially reduced. Part 4.6.4 shows that the final data show much better agreement on sea level accelerations, that the Final Common Mode is robust, and that its interannual to decadal variability comes from a mode common to the eastern boundary of much of the North Atlantic.

Finally in part 4.7 we summarise the results and draw conclusions.

4.2. Data and sources

In this paper we use various observational and model datasets to account for observed variability in the tide gauge time series. The analysis period of Jan. 1958 to Dec. 2018 is limited by the availability of the CS3X tide and surge model (latest version of the Extended Area Continental Shelf tide and surge model, see description below, and https://www.ntslf.org/storm-surges/storm-surge-model). The seasonal cycle was removed from each time series by simultaneous least squares fitting of annual and semi-annual sinusoids (application of this method leads to data described as “deseasonalised” below).

Monthly MSL data (Metric and RLR data sets) for waters around the British Isles (Fig. 4.1) was obtained from the PSMSL (Holgate et al. 2013), https://www.psmsl.org/data/ augmented by other sources. These included the Irish Office of Public Works (http://waterlevel.ie/hydro-data/stations/40060/station.html) for updated data from Malin Head; the Channel Coastal Observatory reports (https://www.channelcoast.org/reports/); (which included data from an additional gauge at Whitby since 2014), data from the British Oceanographic Data Centre (BODC); from recently published research (Haigh et al. 2009) including a long time series from Southampton; and small amounts of additional unpublished “new” data recovered from the National Oceanography Centre (NOC) archives (e.g. small sections of data for Workington, Dunbar and Cromer from the 1970s). The data archaeology exercise covered all periods of tide gauge observations, but in most of the analysis here we use data from the years Jan. 1958 to Dec. 2018 inclusive.

The annual MSL data from a global mean sea level reconstruction (Church and White 2011, updated to 2013) was downloaded from: https://www.cmar.csiro.au/sealevel/sl_data_cmar.html. We also downloaded the hybrid reconstruction of monthly global MSL estimates from Dangendorf et al. (2019) at https://doi.org/10.1038/s41558-019-0531-8. These are already GIA corrected and are used for comparison and global context.

Gridded satellite altimetry absolute dynamic topography at 1/4° resolution from Segment-Sol multimissions d'ALTimétrie, Orbitographie et localisation précise/Data Unification and Altimeter Combination System (SSALTO/DUACS) was downloaded from Copernicus Marine Environment Monitoring System at http://marine.copernicus.eu/ . This product has already been adjusted for the inverse barometer effect (Carrère et al. 2016). Monthly mean equivalent sea surface height (SSH) time series were extracted from grid points near each tide gauge location. These represent local MSL relative to a geocentric reference frame, but the data is only available from 1993 onwards. This data was used for comparison with tide gauge data over the satellite period.

Sea level variability due to local meteorological influence is estimated using CS3X, a variant of the UK's main operational tide-surge forecast model (e.g. Flather and Heaps 1975; Flather 2000; Flowerdew et al. 2010). Modelled monthly mean sea level was extracted from hourly time series of sea level variability due to tide and surge at each tide gauge site, simulated from Jan. 1958 to Dec. 2018. The domain spans 20°W to 13°E, 40°N to 63°N, with a resolution of 1/9° latitude by 1/6° longitude (approx. 12km, see https://noc.ac.uk/files/documents/business/model-info-CS3X.pdf). The open boundaries are forced with an assumed constant sea level plus local inverse barometer response to atmospheric pressure, and tidal constituents from a tidal analysis of an outer CS3X-like model of the northeast Atlantic (Flather 1981). The atmospheric forcing is 6-hourly wind and sea-level pressure from ERA-40 (Uppala et al. 2005) over the reanalysis period (1 Jan. 1958 to 31 Aug. 2002) and from Met Office operational hindcasts from the Met Office operational atmospheric model (Unified Model) thereafter.

We use a GIA correction (Emery and Aubrey 1985; Peltier and Tushingham 1989; Whitehouse 2018) given by the Peltier ICE-6G_C (VM5a) model (Peltier et al. 2015; Argus et al. 2014), available from http://www.atmosp.physics.utoronto.ca/~peltier/data.php. The correction we apply includes gravitational effects as well as vertical land movement, removing the secular component of RSL (relative sea level) that results from GIA (Tamisiea

2011). Other GIA models are available for the UK, (as are CGPS (Continuous Global Positioning System) based estimates of recent vertical land motion). Other models we looked at were similarly effective in reducing the scatter in these trends.

4.3. Summary of Data Archaeology

A data archaeology exercise was carried out using historical documents archived at the NOC (Liverpool), UK Hydrographic Office (UKHO) archives (Taunton) and older editions of large-scale Ordnance Survey (OS) maps (online). These comprised OS levelling records, tide gauge calibration records, annual Admiralty Tide Tables, Institute of Oceanographic Sciences (IOS) and National Tidal and Sea Level Facility (NTSLF) reports, paper records of tide gauge history (e.g. Tide Gauge Inspectorate (TGI) reports) and large amounts of correspondence between the UKHO (and many others, e.g. individual port authorities) and the PSMSL. This resulted in additional information being recovered for each tide gauge site, such as older local bench mark elevations, semi-annual or annual tide gauge zero check sheets, Ordnance Survey tide gauge zero levelling history (summarised in OS-319 sheets, see supplementary material 2), and elevation changes to the local port or chart datum.

The recovery of additional datum connections and bench mark elevations allowed extension or creation of time series referenced to a consistent site datum (RLR-style) at several locations (e.g. Stornoway, Ullapool, Newhaven, Shoreham, Blyth) and new composite series to be created (e.g. Swansea and Mumbles, Invergordon and Buckie, Harwich and Felixstowe, and the two records from Leith) similar to the process used previously for Aberdeen and Liverpool (Woodworth et al. 2009a). In this case the use of Ordnance Datum Newlyn (ODN), or Local Ordnance Datum on island sites aids the comparison of elevations of older and modern benchmarks, and also has the effect of making the absolute levels more comparable between tide gauges, especially locally. We refer to the data after correction to a common reference datum as “reduced” data.

Any average offset adjustments required due to sections of data being Mean Tide Level (MTL) rather than MSL were also made (Suthons 1937; Hogarth 2014; Woodworth 2017). These adjustments vary from station to station and can be centimetre scale. This reanalysed MSL data was checked against the PSMSL RLR time series. Any offset between the reanalysed Metric data and the RLR series should be constant and equal to the difference between the RLR reference elevation and the mapping datum (ODN) given in the

PSMSL RLR diagrams. A small number of anomalies were investigated and resolved or explained (e.g. Portsmouth and Devonport).

A tide gauge 'event' file was created for each site by digitising all recorded physical changes which could potentially affect the tide gauge zero. These were extracted from OS 319 sheets (these are detailed in supplements 4.1 and 4.2), TGI records and correspondence files. This information has been summarised in a MATLAB® script containing change event dates and brief descriptions for each site, indexed by PSMSL site number (see supplementary material 4.3).

The six-monthly or annual measurements of tide gauge zero elevation changes relative to the tide gauge bench marks were also recovered and digitised for the 35 sites where OS 319 sheets were available, as were the equivalent recorded levelling measurements available for Malin Head. 'Calibration' files were created for each site, containing a list of observation dates and measured differences between the measured TGZ and assumed TGZ elevations.

4.4. Method, Case Studies: Data processing steps

4.4.1. Data extension: the PSMSL RLR monthly MSL record for Stornoway (site 46, see figure 4.1) starts in 1977, but there is also a year of Metric data from Nov. 1928, and an almost continuous record from January 1957. The data archaeology exercise allowed recovery of the relative TGZ and bench mark elevations from these additional periods, resolving the large datum steps and thus extending the time over which a consistent datum could be applied by an additional 252 station months, adding another 50% to the existing RLR record (Fig. 4.2). This extension process was repeated where possible for each site around the British Isles, giving a new extended monthly MSL dataset (here reduced to ODN), which we call the "Metric extended reduced" (MER) dataset. This dataset was then deseasonalised and adjusted for GIA using the Peltier ICE-6G_C (VM5a) model (Peltier et al. 2015).

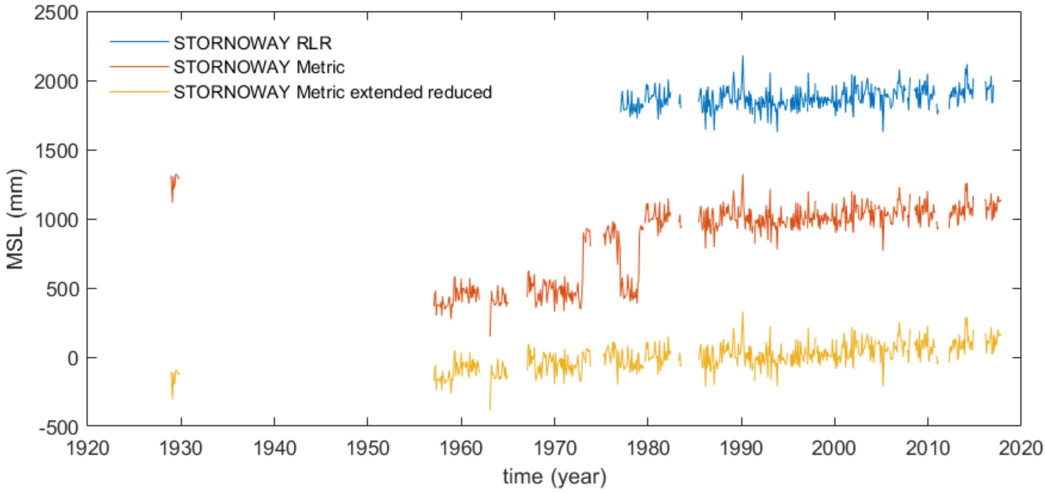


Figure 4.2: Deseasonalised monthly MSL for Stornoway; PSMSL RLR, PSMSL Metric, and Metric extended reduced data using recovered datum connection information. Each time series is offset vertically for visualisation.

The Metric record from Immingham (10) over the Oct. 1959 to 2018 period also has a large recorded datum difference of over 7 m after the end of 1985. This has already been accounted for in the PSMSL RLR record. The site records of tide gauge zero and local bench mark elevations give the relative datum offsets needed to reduce the Metric data to ODN and these validate the elevation values in the site RLR diagram from the PSMSL. However the GIA-compensated SLR trend derived from the Immingham time series is less than 1 mm yr^{-1}, whereas the neighbouring gauges with long and relatively complete time series at North Shields (8) and Lowestoft (12) (approx. 173 km north and 182 km south of Immingham respectively) have trends of over 2 mm yr^{-1} over the same period. The anomalously low trend at Immingham has been previously attributed to known density changes in the river Humber run-off (Woodworth et al. 2009a; Haigh et al. 2009a).

4.4.2. Buddy checking: The time series from Immingham was then 'buddy checked' (Rude 1926; Woodworth 1991) against similarly adjusted MSL records from the two sites above. Fig. 4.3 shows plots of the differences (Immingham minus North Shields and Lowestoft monthly MSL respectively). Taking differences of records from nearby sites effectively removes any additional coherent "common mode" variability (for nearby sites this will include both local and far field effects), revealing several clear steps after year 2000, and two more ambiguous ones before that date. Various techniques were tried to automatically detect and quantify the steps seen. Using the maximum likelihood changepoint detection function implemented in MATLAB® (Lavielle 2005; Eckley et al.

2011; Killick et al. 2012) on each difference plot gives an estimate of the most probable change points in mean difference. If the time and magnitude of any detected changes are the same in both comparisons (within some defined tolerance), then the change probably originates from the shared time series, i.e. Immingham (see also Caussinus and Mestre 2004 for other examples of this methodology). These coincident detected change points are shown as green dashed lines.

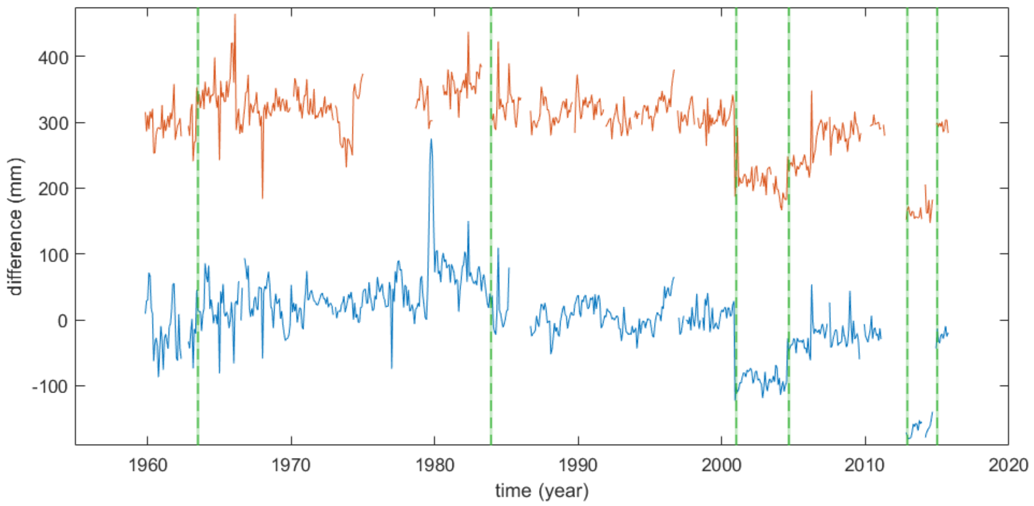


Figure 4.3: Difference plots of reference MSL minus model series from nearby sites, with detected change points. Red: Immingham minus North Shields (offset 300 mm for visualisation). Blue: Immingham minus Lowestoft. Change points which are common to both difference plots are dashed green.

However independent information is needed to confirm the timing of the steps, and the "buddy" checking relies on having good quality and near complete data from neighbouring sites. This is not always available, so various other methods were explored to reduce the variability in the MSL records, including the use of barotropic models and a common mode (Woodworth et al. 1999).

4.4.3. Adjusting for local and far field sea level variability. The top (blue) trace of figure 4.4 shows the deseasonalised monthly MSL data for our case study site of Immingham. The sea level response to local meteorological effects (inverse barometer and wind stress) can be accounted for by subtracting the mean monthly CS3X modelled sea level, which is derived purely from a reanalysis of atmospheric pressure and wind observations.

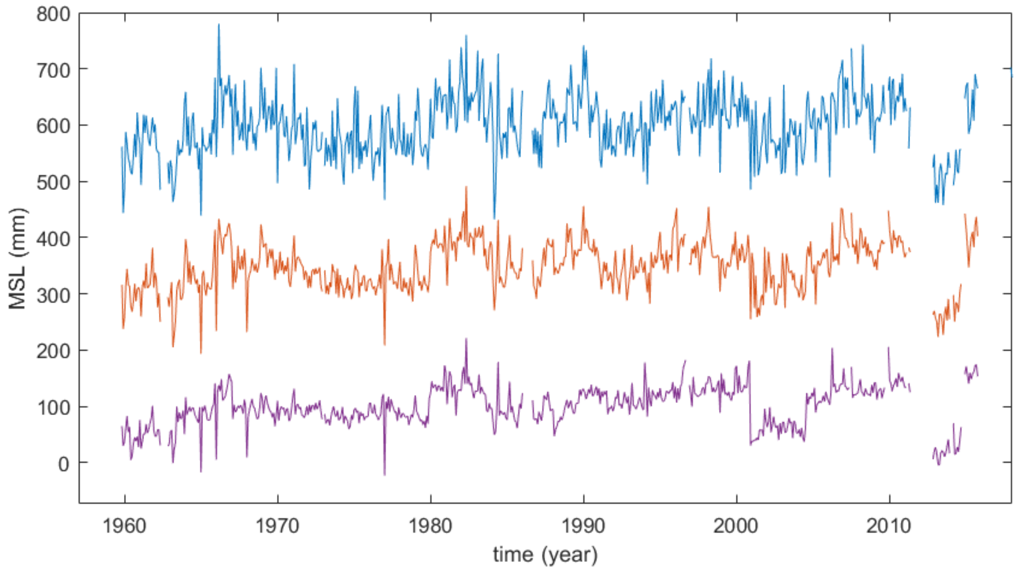


Figure 4.4: Plot showing progressive reduction of variability in monthly MSL time series from top,
blue: deseasonalised MSL data with initial datum adjustments. Red: deseasonalised data adjusted for CS3X tide and surge model. Purple: Adjusted using CS3X and common mode. Each time series is offset by 200mm to aid visualisation.

The middle (red) trace of Fig. 4.4 shows the result. The meteorologically induced high frequency variability is greatly reduced, but lower frequency components remain largely unaffected. This is expected as the tide and surge model itself contains little interannual to multidecadal variability. Comparing with similarly processed data from other sites around the British Isles confirmed that these low frequency fluctuations appear coherent. Consistent with the buddy checking results, removing a "common mode" which contains these low frequency signals (Larsen et al. 2003) results in a further reduction in variability, as shown by the residual in the bottom (purple) trace of fig. 4.4. This Initial Common Mode (ICM) is here defined as the average detrended (first and second order) MSL for all stations, with individual tide and surge model data removed. Note that this ICM is used purely to reduce variability and aid in detection of steps. We will later produce a Final Common Mode (FCM) which retains all trends, and where any potential bias due to averaging different record lengths is minimised (see supplementary material 4.1) and tested by using various combinations of records. It is thought that this "common mode" signal will reflect broader scale ocean variability originating from beyond the local shelf region (Chafik et al. 2019). Unlike buddy checking, this two-step process effectively separates far field ocean effects from local meteorological effects. We find that combining CS3X with a common mode best reduces the natural variability seen at most tide gauges.

Referring to figure 4.4, as the variability is progressively reduced, a number of clear datum steps emerge, e.g. in 2000 and around 2012. In addition, comparing the adjusted time series from neighbouring sites reveals apparent trend similarities in sections unaffected by these steps. This suggests that much of the difference in SLR trend between Immingham and nearby gauges can be explained by the presence of these datum shifts (see also Becker et al. 2009 for trend differences due to datum shifts in records from the coast of Holland). Thus, the subtraction of tide and surge model plus common mode data allows for similar discrimination of steps to that found by high quality buddy checking, but we still require more information to help interpret the steps that are seen.

4.4.4. Identifying and quantifying datum steps. Fig. 4.5 shows the deseasonalised and detrended monthly MSL data for Immingham, with modelled storm surge data and the initial common mode subtracted (blue, see supplementary material 4.1 for detrending method used at this stage).

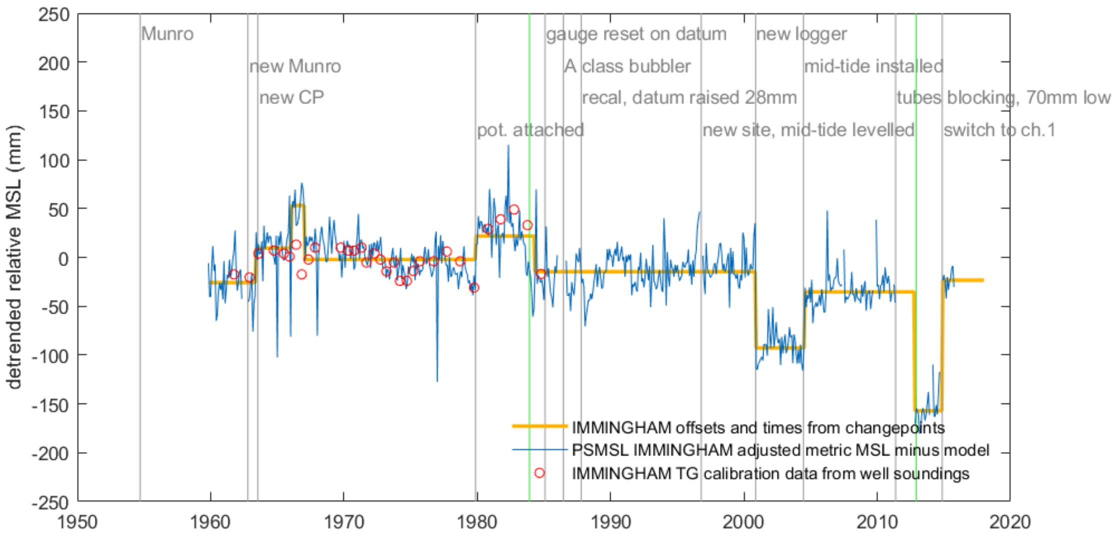


Figure 4.5: Plot of deseasonalised detrended monthly MSL minus surge model and common mode for Immingham. Results of auto change point detection and segment mean values are shown in orange. Recorded physical changes at the site are shown as vertical grey lines with the labels running in groups of four stepping sequentially downwards and to the right. Any additional changes common to two independent buddy checks are shown as green vertical lines. TGZ differences from recorded datum (OS levelling) are shown as red circles.

Initial attempts were made to quantify the step timing and size using a variety of change point detection methods (Beaulieu et al. 2012). Using the Mann-Whitney test and basic differential methods (Trauth et al. 2018) showed false detect issues typical of the 'change point detection problem' (Gallagher et al. 2013). A more flexible and robust method used the MATLAB® maximum likelihood change point function. For Immingham, nine changepoints are detected, as shown by the orange line in Fig. 4.5.

The data archaeology exercise allowed a record of all physical change events which could potentially affect the datum to be created for each site (supplement 4.3). For Immingham these are shown as grey vertical lines in Fig. 4.5. Importantly, many of these events are associated either with breaks in the time series, or apparent datum shifts. Many of the detected changepoints (orange) are seen to coincide with recorded events (grey), as well as the independent results of the buddy checking from the two other sites illustrated previously. The buddy checking process also gives some additional changepoint times which were unrecorded (e.g. late 1983). These are shown as green vertical lines in Fig. 4.5. We find after reviewing all sites that the recorded events augmented with the buddy checking results capture the times of almost all visible datum shifts, and the majority of changes detected using the maximum likelihood function. We also investigated a number of high resolution records (15 minute sampling) which confirmed that steps were usually associated with breaks in data continuity, implying a physical change. Thus, these recorded events, and those buddy-checking steps which are confirmed by the model-based jump detection, give us an objective set of break points at which we should seek information on datum changes (Li and Lund 2015). We only consider detected jumps which are confirmed by at least one other source of information. These are then referred to below as "events".

4.4.5. Adjusting for datum steps. For Immingham, semi-annual or annual tide gauge zero reference (Van de Casteele tests, Lennon 1968) and repeat levelling measurements by the OS are available from the early 1960s to the mid-1980s (OS 319 sheets, see supplementary material 4.1 and 4.2 for explanation and examples). These record some of the known instrumentation changes. Normally a time average of these levelled calibrations was used by the UKHO and PSMSL to define the TGZ. The discrete 'calibration file' offset values for this site are plotted as red circles in Fig. 4.5. These represent the differences between the accepted TGZ value used by the PSMSL (usually the UKHO "Admiralty Chart Datum" based on some fixed definition of observed Low Water level) and the measured TGZ elevations. As has been demonstrated previously in the case of Portsmouth (Webber and Walden

1981; Walden et al. 1982; Haigh et al. 2009), additional information is available which has not been fully exploited. In this case, datum level changes around 1963 and 1980 appear to be recorded, and evidence for a downward step in late 1983 from the buddy checking is validated by a measured elevation change.

We investigated several ways to use the sparse calibration data to adjust the monthly records (e.g. using interpolation between the calibration dates), but after reviewing the results from all sites we concluded that the most robust method was to use an average of the calibrations over each period between ‘event’ times (i.e. the levelling information is used, but averaged over segments of data between our confirmed change points). Applying these offsets (table 4.1) corrects the section of relatively high data between the end of 1979 and 1983 so that it is no longer discernible (or detectable, Fig. 6). By contrast, the short upwards excursion in 1966 is unaffected. This latter anomaly is also visible in nearby tide gauge records, so is likely to represent real local sea level variation (which might otherwise be removed by a naïve change point detection process).

Several datum shifts are also visible after a bubbler gauge was installed in July 1986 by which time TGZ levelling checks had become intermittent. Nonetheless, some segments, in this case those up to the year 2000, do have levelling data associated with them (note the levelling which is recorded along with the installation of a new site in 1996). As with the regular calibration period, these segments are also ‘fixed’ with reference to ODN using the average of the levelling and calibration data over those segments.

Other segments (in this case all those after the installation of a new logger in 2000) are considered here as “free floating”. The magnitude of corrective offsets for these “free floating” segments can be estimated by a number of methods (table 4.1): by using mean differences for short sections before and after each change event (purple curve in Fig. 4.6); or by buddy check comparisons; or by allowing each segment of data between known change events over the entire extent of the record to be offset and fitted to a best fit (least squares regressed) linear trend and second order function (blue curve in Fig. 6). The second order term was included as it best explained the largest proportion of the low order non-linearity apparent in the majority of longer series, and retaining this signal in each processed series is of interest (a similar rationale is behind the ICM being quadratically detrended).

4.4.6. Validation. A comparison of these independently derived step offset values (Table 4.1) can give some measure of confidence in each estimate. For example for December 2014 the change detect method gives an estimated positive step of 136mm, the buddy check comparisons give 130mm and 139 mm respectively, whilst the surge model difference and regression both give 133mm. An additional check with the high quality record (Bradshaw et al. 2016) from more distant Newlyn gives 105 mm. The comparisons for the change point detect and buddy check also show some differences in timing of the steps as the unconstrained estimate of change time also has uncertainties. Comparisons can also be made for the period from 1993 onward with gridded satellite altimetry data, provided that variability due to meteorological effects is similarly minimised. For Immingham the adjusted TG minus local altimeter MSL trend is 0.025mm yr^{-1}, whereas the unadjusted TG minus altimeter MSL trend is -3.7mm yr^{-1}. The adjustment process will thus greatly impact estimates of VLM based on TG minus altimetry data, where the effect of datum shifts in the TG data on the residual trends is compounded by the relatively short altimetry period.

Year: Event	1963.62	1979.96	1983.96	2000.96	2004.46	2012.96	2014.96
Using cal. and regression	**24**	**48**	**-55**	**-79**	55	-123	133
Offsets from Surge Model				-79	48	-157	133
Year: changepoint detect	1963.46		1983.71	2000.96	2004.62	2012.87	2014.96
Offsets: changepoint detect	35		-51	-78	60	-119	136
Year: Buddy check	1963.54		1983.96	2001.04	2004.71	2012.96	2014.96
Buddy check North Shields	46		-39	-94	49	-129	130
Buddy check Lowestoft	42	59	-55	-96	62	-143	139
Buddy check Newlyn	42	49	-51	-100	57	-133	105

Table 4.1: Top: Offsets (mm) for Immingham derived from calibration up to 1984, and levelling (bold) combined with regression after 2001. This is the method used in this analysis. Next two rows, offsets derived from differences between data and modelled sea level for 36 months before and after event. Next, offset and time estimates from changepoint detect process. Bottom three rows, offsets and mean time of detected changes for buddy checks for three long and relatively complete records.

The offset adjustment values used for this paper are the calibration results (For Immingham, table 4.1, top row) over the period these are available (approximately the first half of the record in this case), and the levelling constrained regression results over the rest of the record. All series have seasonal, GIA, surge model and common mode adjustments.

The time series after step removal more closely resembles those of other sites on the East Coast which appear to be less affected by datum shifts, as shown in the comparison with Lowestoft and North Shields in Fig. 4.6.

While this process is useful for unifying the time series, it is important to bear in mind the difference between those segments of data which have been fixed by levelling (offsets in bold for table 1), and those which have been adjusted based on some kind of reasonable expectation of short term consistency (smoothness) of the difference between measured and modelled data. It is also important to contrast the differences between this "event" constrained approach and unconstrained approaches based on changepoint detection. Initial attempts at blind step detection showed this naïve approach will inevitably remove low frequency components of natural variability as well as steps if the magnitudes of the low frequency fluctuations are similar to or greater than that of the datum steps. We show later that this step adjustment is less of a problem when the step times are limited to confirmed events.

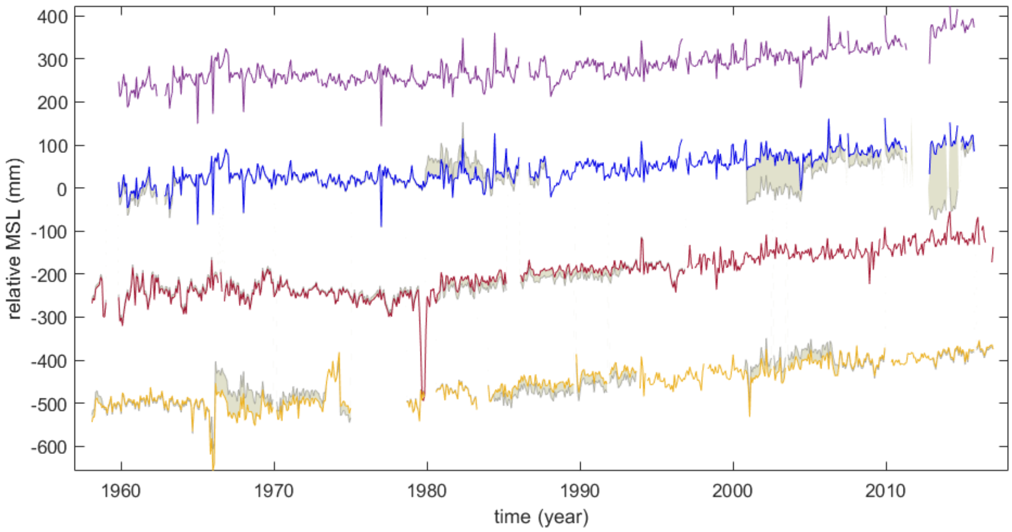


Figure 4.6: Top, purple: adjusted Metric MSL data for Immingham, result of subtracting the individually estimated offsets derived from mean difference values for up to three years either side of each change. Blue: adjusted Metric MSL data for Immingham, result of alternative datum step adjustment using calibration data up to 1984 and segment-based regression thereafter. Grey shading shows data before adjustment and magnitude of correction. Red and orange show North Shields and Lowestoft respectively, treated in the same way with the relatively small datum adjustments for these sites again in grey. The

negative spike in the Lowestoft record just before 1980 is normally flagged as an error and removed in the RLR record. Each time series is offset 250mm for visualisation.

This section has illustrated the approach in the context of two particular tide gauges. In the next section we summarise the various stages as applied across the wider range of gauges from around the British Isles. We will show later that this results in improved consistency between long term trends measured at these sites.

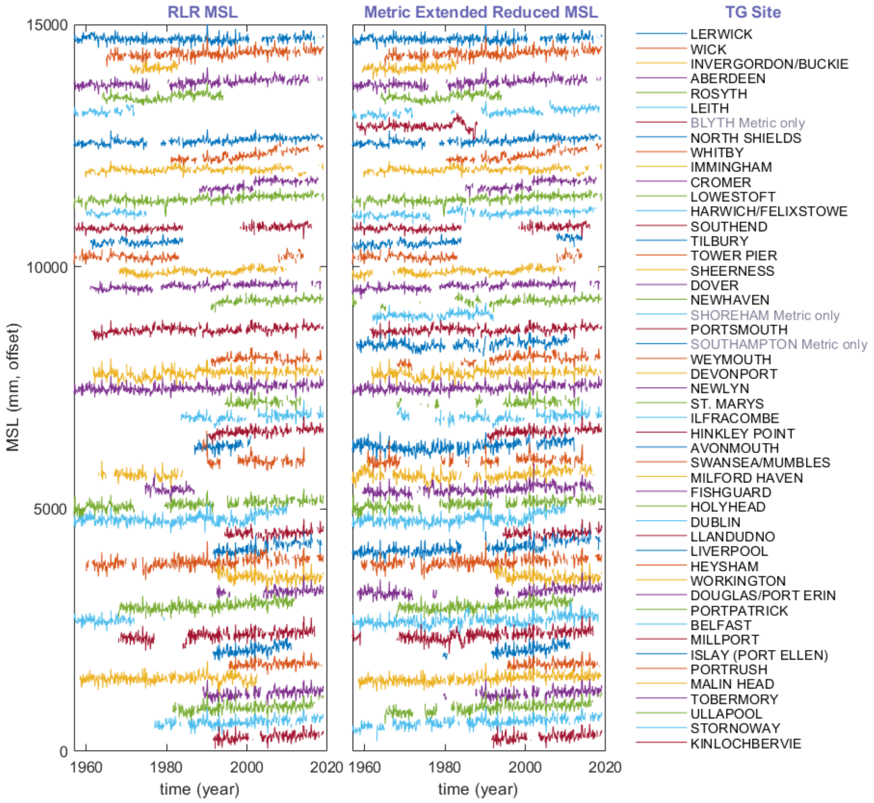


Figure 4.7: RLR monthly MSL from PSMSL compared with Metric extended reduced MSL Jan. 1958 to Dec. 2018, deseasonalised and adjusted for GIA (49 sites with a span of more than 20 years of extended data shown here). Each series offset by 300mm for visualisation. Data steps are not immediately apparent at this stage.

4.5. Application to all tide gauges around the British Isles

4.5.1. Extending RLR data where possible. The process described for Immingham was automated and repeated for all sites. The first stage is to independently replicate the Metric to RLR conversion performed by the PSMSL, but using the extended information and metadata provided by the data archaeology initiative. The results of this are shown in Fig. 4.7 compared with RLR data. Newly reduced data comprise 9542 station-months in addition to the 22485 station-months already in the RLR dataset for the sites studied, a 42% increase in available data, including some data not in the PSMSL Metric dataset (e.g. from Southampton and Belfast). A graphical overview of the extent of the various MSL data used is also given in Fig S5 in supplement 4.1. Any large "spikes" (see Fig. 4.5) which are normally flagged in RLR data were identified using a modified version of the function described in Feuerstein et al. (2009), where the spike data values were removed rather than replaced with interpolated values. Tower Pier (a station on the river Thames in the Greater London area) was rejected at this stage due to high variability associated with run-off causing river level fluctuations which were not captured in the tide and surge model, giving 48 stations (Fig. 4.1). For each site, a list of recorded instrumentation changes was also created from the data archaeology exercise.

4.5.2. Buddy checking. We now perform buddy checking. This helps initially to identify some likely datum shifts. Where two buddy stations show a coincident datum change of similar size, the majority of these are also found to coincide with known instrumentation changes at the common site. A small number of coincident buddy check steps are found not to be associated with known changes, but most likely reflect an unrecorded event. For these, the timing is derived using results from the change point detection averaged for both buddy check difference series. These times are then used to augment the recorded event times in order to objectively capture all independently detectable step changes.

4.5.3. Adjusting for local and far field sea level variability. Following this, the local modelled GIA trend and detrended modelled monthly mean tide and surge response plus common mode were subtracted from the tide gauge data for each site. The maximum likelihood change point analysis was applied to again help identify potential steps. As with Immingham, it is clear that datum steps exist in a number of records, and that these are responsible for significant long-term differences in trends between gauges. Those steps which had independent confirmation, mostly from documented instrumentation changes but in some cases from buddy checking, were used to create event files for each site, and these event times were used to divide the data into segments for adjustment.

4.5.4. Identifying and quantifying datum steps. The tide gauge levelling and calibration results from OS-319 sheets (supplementary material 4.2) were then digitised for the 36 sites at which they were available. The equivalent levelling information was also digitised for Malin Head on the Irish Coast. Records from some of the sites where calibration data is available (e.g. Harwich and Felixstowe) have been merged into longer composite MSL records. A small number of sites have calibration data but no available MSL data. This reduces the number of sites where systematic calibration results can be used to 33 (Fig. 4.8), and of these, only 28 have more than 20 years of data (centre panel Fig 4.9). The measured TGZ values were double checked against the original Van de Casteele calibration test results (see Lennon 1968) and bench mark information (see supplementary material 4.1).

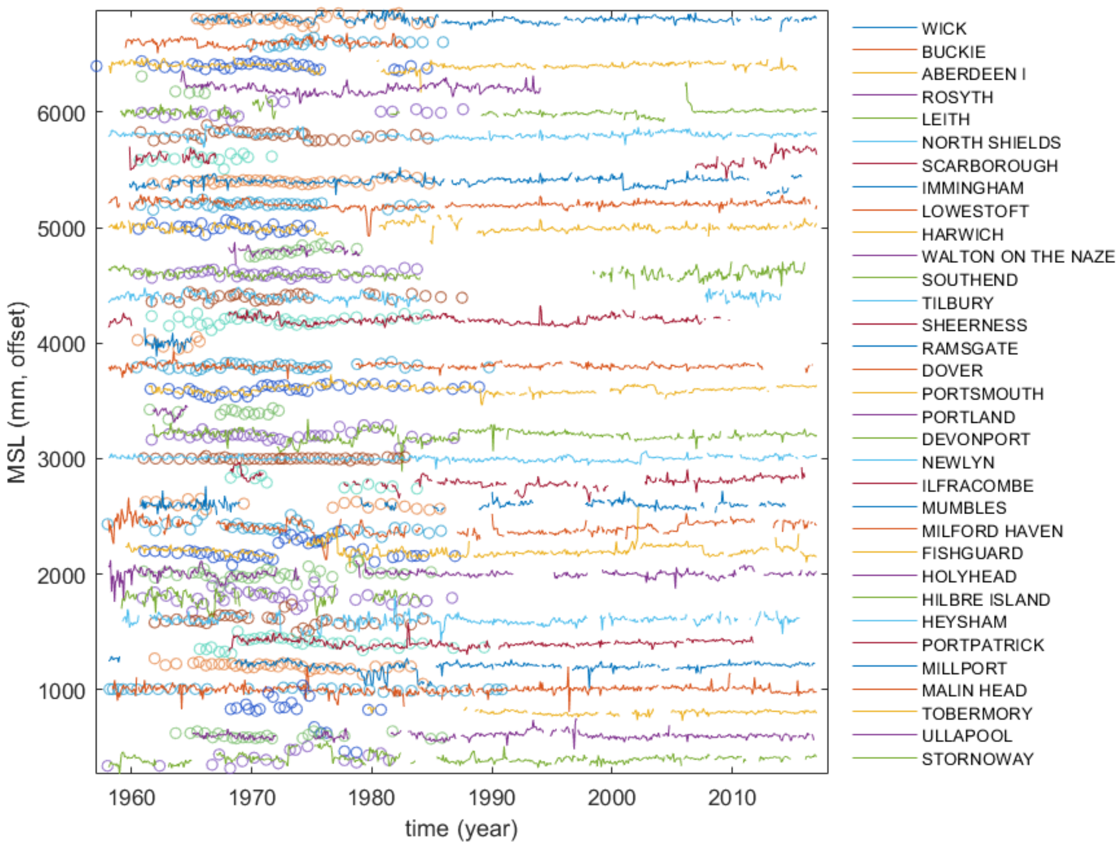


Figure 4.8: Data from 33 sites with overlapping TGZ calibration and MSL data. Tide gauge zero calibration results (circles) overlaid on detrended monthly MSL time series with surge model data and common mode subtracted. Inspection shows correlation at interannual timescales implying some lower frequency variability in apparent MSL is due to variability of recorded TGZ setting.

4.5.5. Adjusting for datum steps. The levelling results were then applied to those site-segments for which they were available (generally covering the period from the early 1960s to the mid-1980s), and then "free floating" segments were adjusted by least squares fitting a linear and quadratic trend plus offsets to each series of the entire dataset, with offset adjustments only permitted on the "free floating" segments (Fig. 4.9). As with Immingham, not all post 1980s segments are "free floating", for example many segments are "fixed" using levelling information related to the installation and calibration of mid-tide sensors (Woodworth et al. 1996).

In summary, each residual tide gauge time series (with surge model and ICM subtracted off) was cut into segments bounded by fixed "event" times. These events are defined as times of documented equipment changes, with occasional additions where dual buddy checking gives additional times. These were then checked against the results of an automatic step-detection process. Levelling information was used to fix the datum in all segments for which it was available (coloured segments in the right hand panel of Figure 4.9). Other "free floating" segments were then offset so as to minimise the difference from a quadratic fit to the data which are not "free floating", and the offset values were independently buddy checked. The quadratic trend of each time series is therefore determined only by the levelled segments. As a further independent check, the sections of time series from 1993 to 2017 were then compared with the 0.25 degree gridded altimeter monthly mean MSL data, using both the nearest grid cell and an average of nearest grid cells to each tide gauge. The overall processing steps are shown graphically in Fig. S6 supplement 4.1.

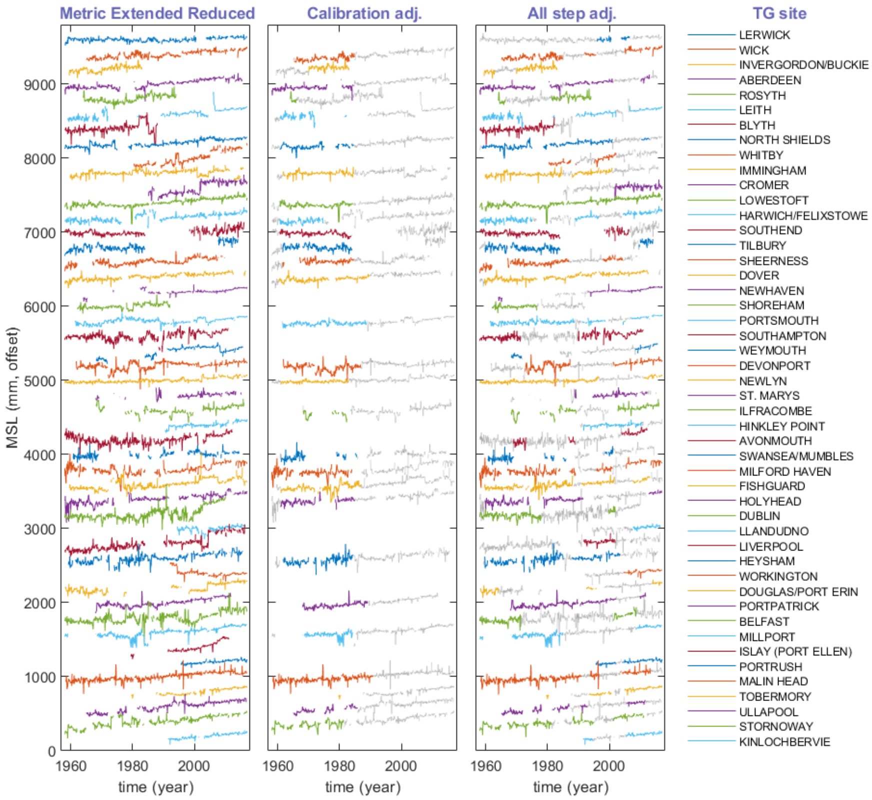


Figure 4.9: Metric extended reduced monthly MSL time series for 48 sites with over 20 years of data from Jan. 1958 to Dec. 2018. Left panel: adjusted only for seasonal variation, GIA, surge model data and common mode. Centre panel: data for 28 sites with more than 20 years of data and where TGZ calibration data is available. Calibration corrections are applied to the coloured sections (grey sections are unadjusted at this stage). Right panel: data from all sites, coloured where calibration and documented levelling information are available. These segments are fixed, whilst remaining segments (grey) are adjusted, here using a regression method.

The final step offset values (the signals to be subtracted from each record to correct for datum jumps) referenced to the nominal TGZ for each site can in some cases exceed 100 mm (Fig. 4.10a). Any impact of the average datum correction signal (Fig. 4.10b) on the existing mean SLR trend for the British Isles will be small as there is little correlation of data step times or magnitudes between sites, and the resultant pseudo-noise averaged offset signal has little bias (here, the small -0.1 mm yr^{-1} negative trend introduced by datum steps means that, after correction, the adjusted trend is increased by +0.1 mm yr^{-1}). Similarly the small acceleration term in the error signal will reduce the acceleration slightly in the final averaged result (see Table 4.2).

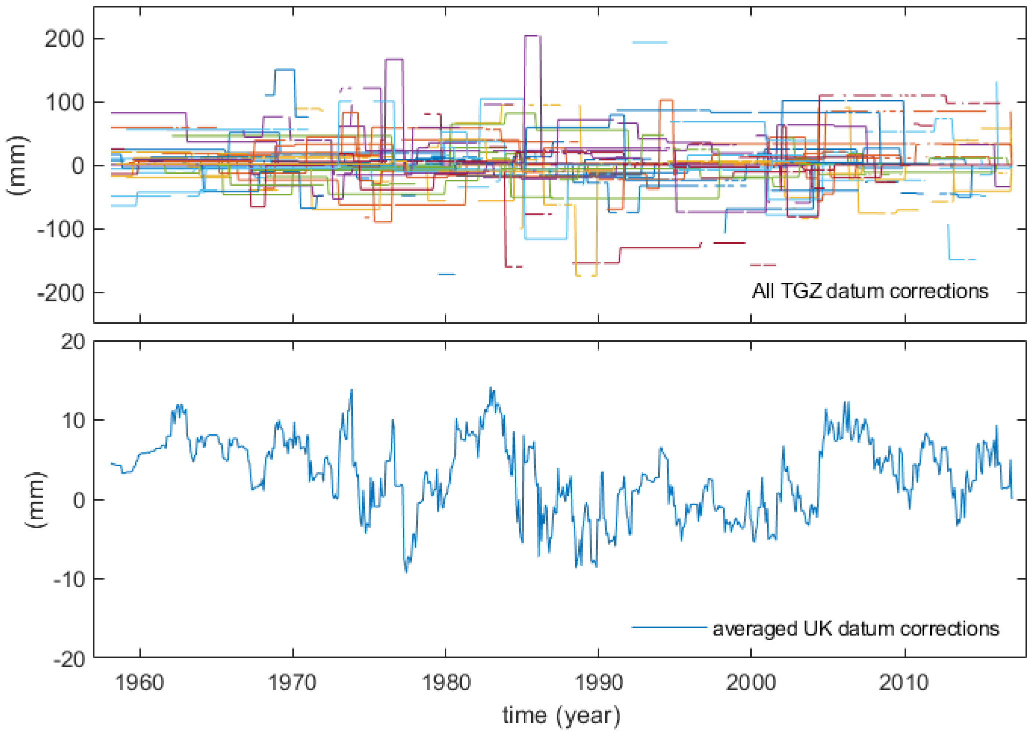


Figure 4.10 a and b: Upper panel (a) shows additional offset correction values (to be subtracted from the original data) for each individual site referenced to nominal TGZ, overlaid. Lower panel (b) shows average of all sites (note different vertical scale).

4.5.6. Trend analysis: New SLR trends and formal uncertainties were then derived. We accounted for coloured noise in the trend fitting process by using the CATS (Create and Analyse Time Series, Williams 2008) software on each time series (Williams 2008; Bos et al. 2013). The effect of the datum step adjustments at individual stations can be profound, in some cases even reversing the SLR trend, as at Workington (37) (Fig. 4.11). Here uncorrected negative steps are apparent in the record, two of which have been previously noted (Hames et al. 2004). Initial tape measurements were made by divers from underwater pressure ports to a fixed point above water during installation of the pressure-based system in 1992, and later datum “corrections” are recorded in September 2002 and June 2004, but only the latter involved levelling to OS bench marks. A naïve interpretation of the unadjusted data would conclude that sea level was falling at this site. The reconstructed data with offsets adjusted assuming the final segment only is fixed has a trend which closely agrees with that from other sites.

The trends for the majority of sites derived in this systematic manner are now more comparable to those derived from the small number of RLR sites typically selected and judged to be of high quality (this has been partly a subjective expert assessment to date) (Woodworth et al. 1999). A few sites appeared not to fit the general pattern, these were found to be associated with factors such as jetty subsidence (e.g. Islay (41)), although for some sites anomalous changes in apparent relative sea level previously attributed to subsidence could be re-assessed in the light of the detected datum shifts.

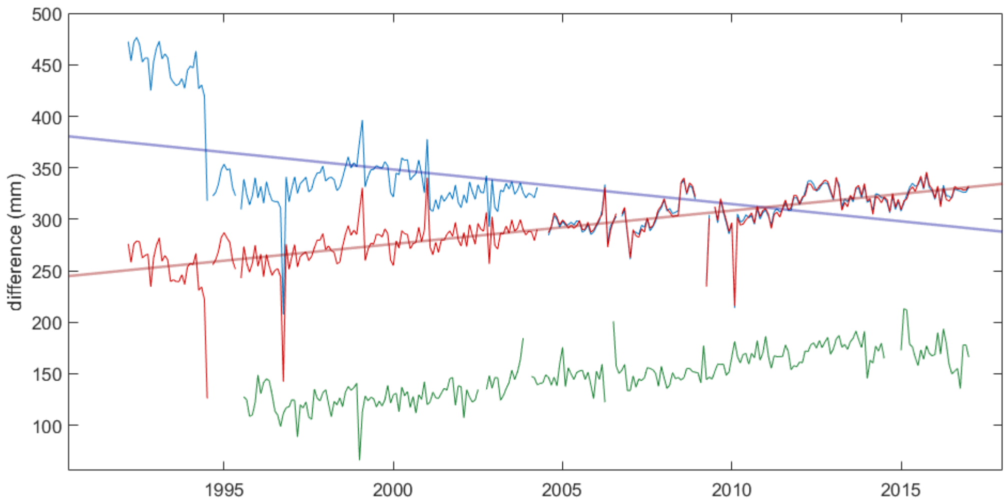


Figure 4.11: Monthly MSL for Workington (blue), adjusted for seasonal variation, GIA, meteorological variability and Initial Common Mode, showing three distinct steps, which contribute to a linear trend of -4.2 mm yr^{-1} . Red: result after step adjustment based on regression, with a revised trend of 2.4mm yr^{-1}. Green: Unadjusted record for Portrush (offset) shown for comparison.

4.5.7. Troublesome cases. A small number of the tide gauge time series remain problematic. For example gauge malfunctions are recorded at Malin Head between 1998 and 2003, and these correspond to lowered MSL anomalies in the data (Fig. 4.12, blue). These sections of data are probably irredeemable and should be flagged and removed from any trend analysis (as some of them already are in the PSMSL RLR data), but this leaves considerable gaps. A more continuous representation of local MSL can be created by replacing the problematic section using data from nearby working gauges. As with any composite series, this depends on land motion and datums at the original and buddy check site being known. If the infill section overlaps unaffected data and differences are within acceptable error bounds, this gives confidence that this is a reasonable processing step. For Malin Head (44), the bubbler gauge record from Portrush (43) can be used (Fig. 4.12, red) which would otherwise be too short to contribute to the site by site multi-decadal analysis (as it starts in 1995). This also provides evidence for the small datum shift detected in the Malin Head data at the beginning of 2013 (Note that the Malin Head data from 2003 onwards is not yet in the PSMSL, but is available elsewhere, see data section previously)

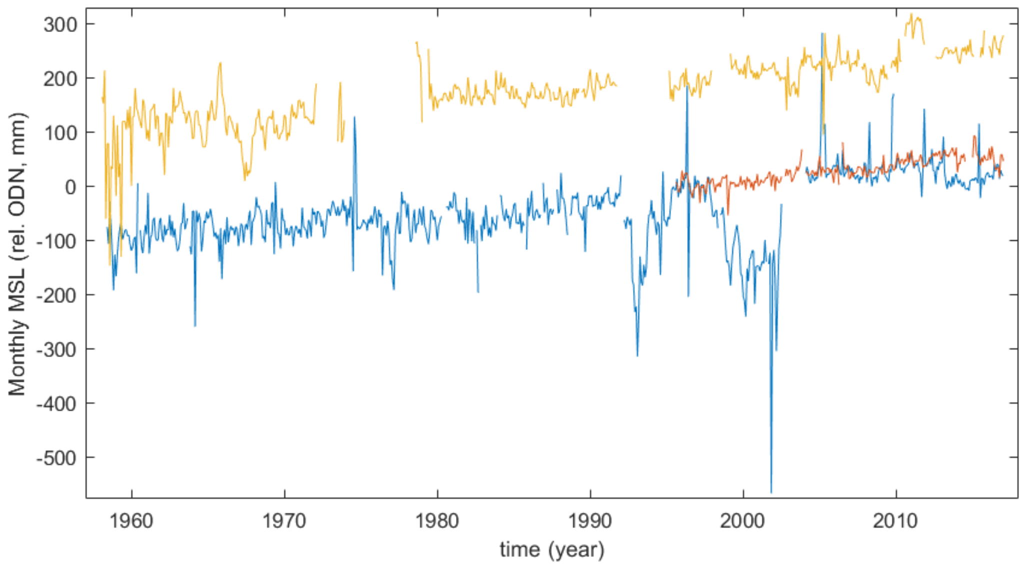


Figure 4.12: Monthly MSL for Malin Head (blue) and Portrush (red), and Holyhead (orange), distance 46km and 288km from Malin Head respectively, all to relevant OD. The data from Portrush can be used to replace part of the erroneous data from Malin Head. The new composite series appears to be consistent with those from several other sites.

For sites such as Southampton (21), Dublin (33) and Belfast (40), sections of relatively high variability indicate low quality data and/or poor datum control. Belfast in particular displays cm-scale step like discontinuities and nonlinearities which cannot be accounted for using existing metadata. At Islay (42) the SLR curve appears smooth, but the SLR and Sea Level Acceleration (SLA) trends are anomalously high, which can be explained by the jetty subsidence reported by the TGI at this site. Without additional measurements of this subsidence, little can be done to correct the data. For Avonmouth (28), the overall record appears to show anomalously high SLR acceleration, which is likely to be due to one or more unrecorded downward datum shifts in the 1960s. For Devonport (23), the tide gauge levelling measurements account for all but one large datum step (around 70mm) associated with a re-siting of the gauge (which would again lead to larger SLR acceleration). This can however be resolved by a single buddy check comparison, as has been done previously over the entire record (Haigh et al. 2009). Despite these issues, apart from

Tower Pier (see previously), only Islay and Belfast were judged to be so extreme as not to be used in the overall trend analysis, reducing the number of sites to 46.

Some of the series with slightly less than 20 years of data (analysed but not included in this paper) also show likely symptoms of subsidence or gauge movement, such as Newport (on the other side of the Avon estuary from Avonmouth (28)) and Scarborough (South of Whitby (9)). At Scarborough vertical movement of the structure at the gauge site is the most likely cause of the apparent SLR being higher than at other East Coast sites. This is supported by evidence from a second more recently levelled gauge elsewhere in the harbour (run by the Channel Coastal Observatory), as there is now a vertical offset between MSL data from the two gauges, despite both being originally referenced to the same datum.

4.6. Results and tests of robustness.

4.6.1. Reduced variability. Despite the overall large month to month MSL variations (Fig. 4.13), the spread of MSL values (here detrended for linear and quadratic terms) for each month for all sites is considerably reduced compared with uncorrected data. This would be expected if the correction process was effective and the MSL was highly coherent at regional scale over a wide range of frequencies. Fig. 4.13 shows detrended MSL for all stations overlaid after removal of step offsets, optical density is related to the degree of time series overlap (commonality). The middle trace shows the same data after the CS3X data (from the nearest grid cell) is removed at each station. The bottom plot shows the effect of removing the common mode signal from each time series. Here the median (red), first and third quartile (yellow shading), as well as the maximum and minimum values (grey envelope) are plotted. This suggests that if local meteorological effects (atmospheric pressure and winds, represented by the tide surge model), any large scale variability due to ocean fluctuations (represented by the common mode signal), linear (GIA and SLR) and second order terms (including any SLR and VLM rate changes) are accounted for, then the residual has little remaining variability or higher order terms. Tests confirmed that removing a degree 2 (quadratic) polynomial from each time series reduced temporal aliasing from the different periods of data available at each site rather more than just removing a linear trend, but that adding additional higher order products made little difference to the final result.

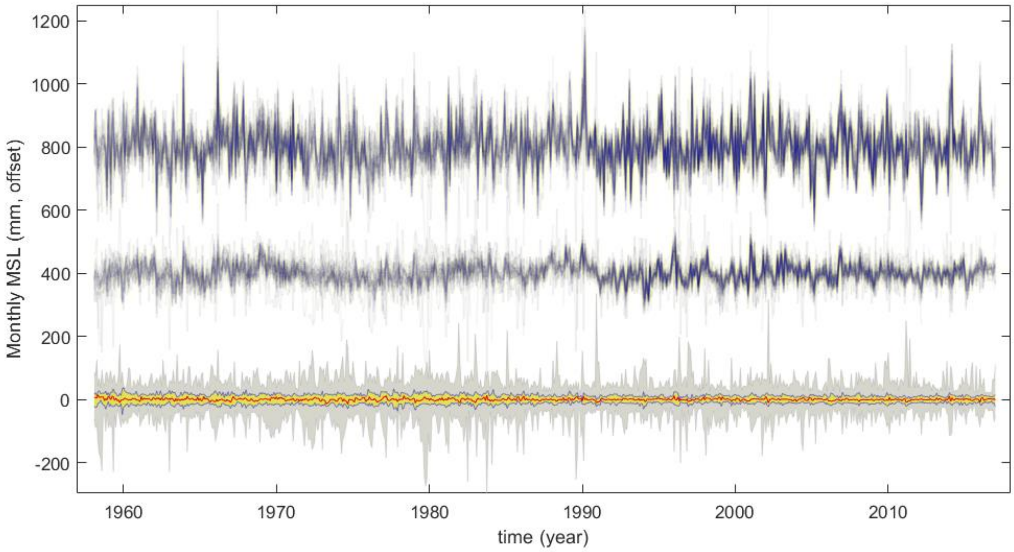


Figure 4.13: Top trace, overlaid detrended (1st and 2nd order), deseasonalised MSL time series with mean offset removed for all sites. Optical density is proportional to number of coincident time series. Middle trace is the same but with storm surge model removed for each site. Bottom trace is with common mode signal removed, and median, 1st and 3rd quartile as well as max/min envelope shown.

The total variance of the original deseasonalised and detrended monthly MSL time series can be viewed as made up of these main components as in Fig. 4.14.

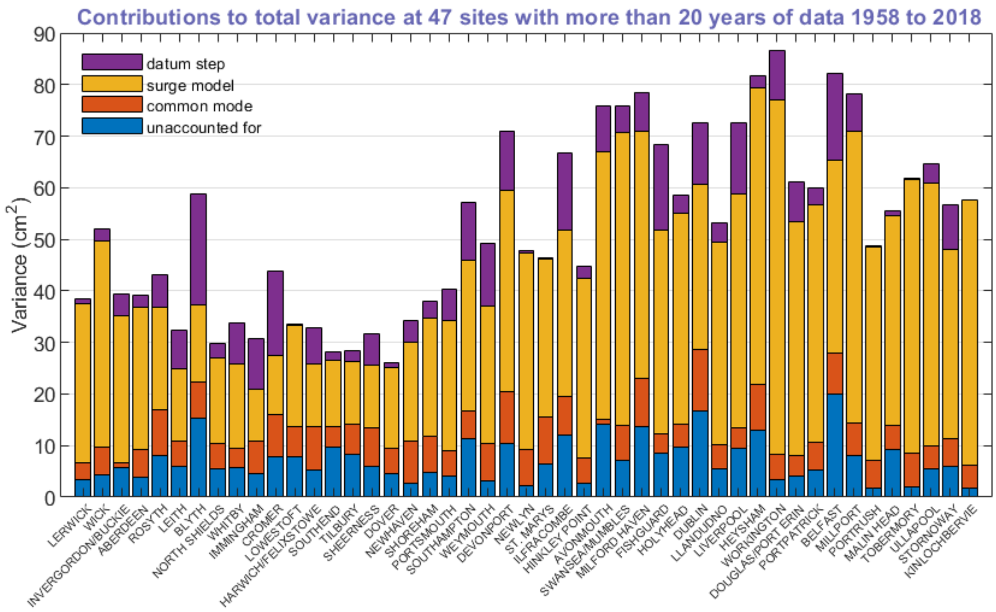


Figure 4.14: Contributions to total variance of deseasonalised monthly mean MSL at each site. The smaller contribution of the surge model and lower variance on the East and South-

East Coasts reflect wind driven processes. The difference is similar to the results found between the East Coast of the UK and the Western European Coast using low pass filtered data (Frederikse et al. 2018).

The residual variance (blue) is in many cases smaller than the variance explained by the datum steps (purple), showing that these were the dominant error source at many sites.

The middle and bottom curves of Fig. 4.13 together demonstrate that, in addition to the removed quadratic trend, there is interannual to interdecadal variability which is common to most of the tide gauge records; i.e. a strong common mode. It is also notable from the bottom curve that the residual variability reduces over the period studied (Fig. 4.13). Possible explanations include improved data quality (Lennon 1970) as new gauge technology (Pugh 1972; 1981) replaces older mechanical gauges in the late 1980s, along with a change to a single data supplying authority, and improved model accuracy as more and higher quality meteorological observations are assimilated into the forcing for the tide and surge model. Another factor is the varying number of gauges contributing, which increases in around 1990, reaching a peak around 2010 after which there is a rapid decline (Fig. 4.15).

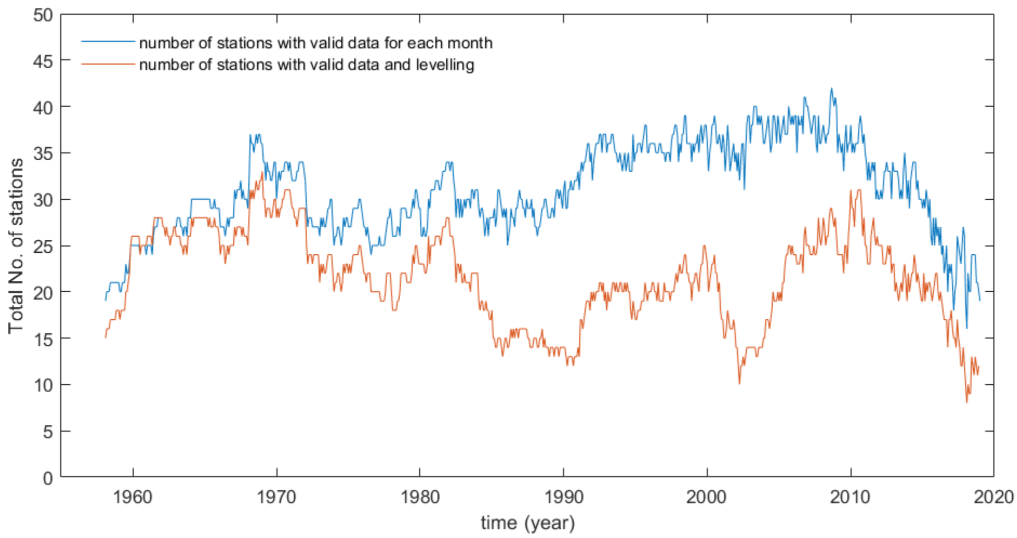


Figure 4.15: Blue: total number of sites with valid MSL data per month Jan. 1958 to Dec. 2017. Red: The number of these sites which also have robust levelling information.

4.6.2. Constraining step adjustments. Any step removal process runs the risk of artificially removing long period variability. In Fig. 4.16 we demonstrate that, by only permitting adjustment of “free floating” segments, we minimise this problem in our analysis. The final data (bottom curve) retains the interannual variability of the original data (top), while reducing the scatter around that variability. In contrast, application of a naïve method which automatically corrects all steps above a threshold without regard to independent levelling information (middle curve) results in a significant reduction of this common mode variability.

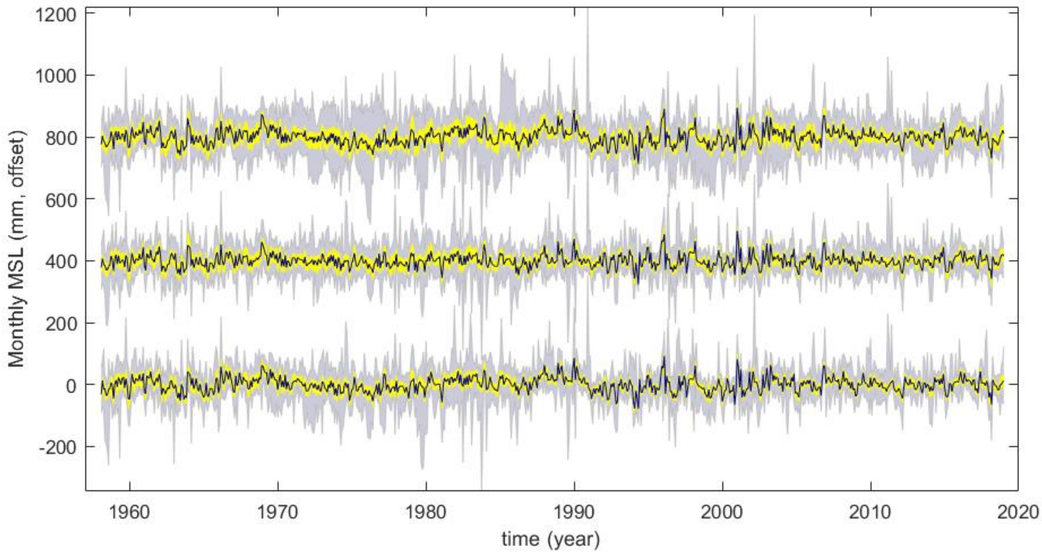


Figure 4.16: Top trace, overlaid detrended (1st and 2nd order), deseasonalised unadjusted MSL with mean offset and storm surge model data removed for all sites. Median, 1st and 3rd quartile as well as max/min envelope shown. Middle trace is the same but with detected steps removed using maximum likelihood change detection. Note some low frequency variations are also removed from the mean. Bottom trace is with datum steps removed using levelling data and event time regression. Note low frequency variability is retained whilst envelope and interquartile spread are reduced to similar levels as middle trace. Each trace is offset 400 mm for visualisation.

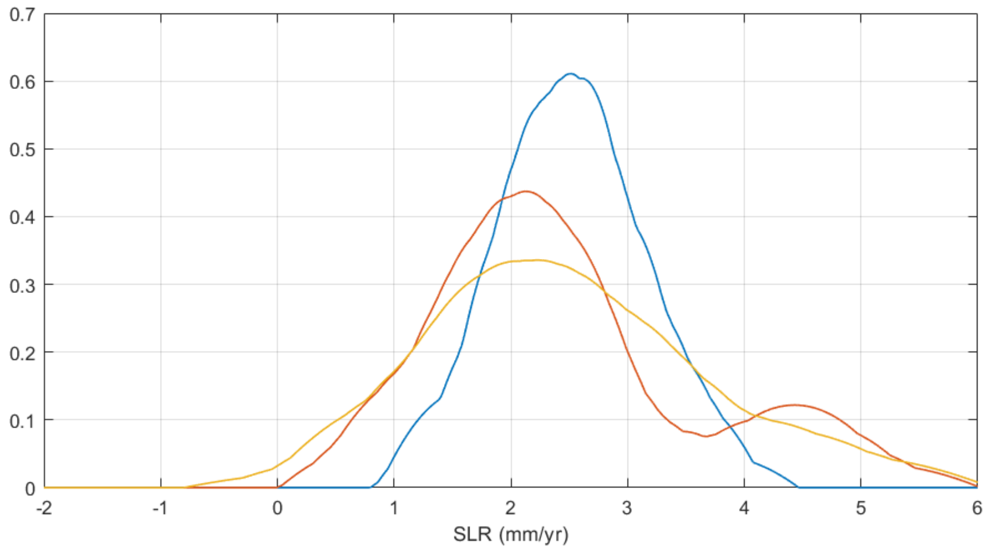


Figure 4.17: PDF of SLR trends from 24 sites with more than 50 years of monthly MSL data and 75% completeness. Yellow: only GIA correction applied. Red: GIA and storm surge model correction and Initial Common Mode applied. Blue: GIA, tide and surge model plus ICM, and step corrections applied.

4.6.3. Improved trend correlation. Fig. 4.17 illustrates the improved homogeneity of trends for time series with at least 50 years of data over the Jan. 1958 to Dec. 2018 period after this process of data correction has been applied independently at each site. We selected 50 years as a compromise between maximising the number of sites and ensuring the observations were over a near identical long period to minimise effects of different start or end times. The CATS software is used for all trend analysis. The probability density function (PDF) plot, uses the Epanechnikov smoothing function also available in MATLAB® (Epanechnikov 1969; Bowman and Azzalini 1997). Numerical values for the SLR trends and uncertainties for each site are given in supplementary material 4.1. Due to the presence of coloured noise the uncertainties are larger than if white noise is assumed (Bos et al. 2013).

Note that, while the correction of “free floating” data segments will tend to reduce interannual variability, it is not biased in its representation of either linear or quadratic trend, which could be made less consistent with other records if the method was not effective. The improvement overall suggests that there are sufficient segments with levelling data to constrain the curves well. The results are consistent with the idea of uniform regional long term underlying trends and low order decadal and multi-decadal variability having long spatial coherence lengths and therefore being highly correlated along coastlines at regional scale (Hughes and Meredith, 2006; Woodworth et al. 2009a;

Wahl et al. 2013; McCarthy et al. 2015). They show that, although GIA is important, the correction of steps has the greatest impact on unifying observed trends around the coast.

As a check of whether the corrections are still valuable over the later period when much less levelling information is available, we compare trends over the 1993-2017 period with those from satellite altimetry (Pfeffer and Allemand 2016; Kleinherenbrink et al. 2018), choosing either the nearest altimetry grid point or an average over all points within around 100 km of each gauge. Note that we take care to match the GIA corrections, applying a correction for both vertical land movement and gravity at the tide gauges, but only the gravity effect for the altimetry. Fig. 4.18 confirms that the corrections improve consistency with satellite altimetry over this period.

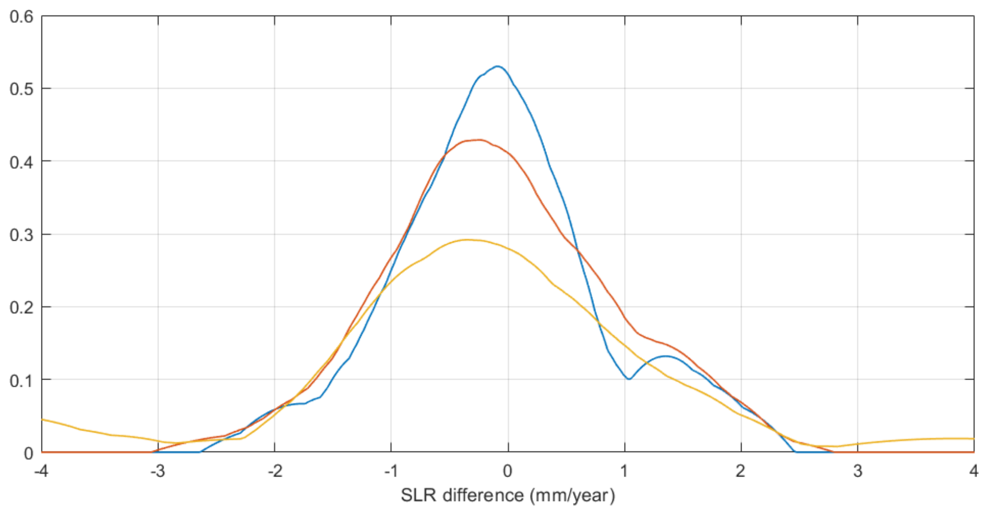


Figure 4.18: PDF plots of deseasonalised and GIA corrected MSL trend differences, tide gauge minus multi-mission satellite altimetry for 30 sites around the British Isles which have at least 20 years of data available over the altimetry time period (1993 to 2017). The tide gauge data is adjusted for storm surge and common mode signal. Orange: difference of TG (adjusted for storm surge and common mode signal but without datum steps removed) and nearest altimeter grid cell trends. Red: same as previous but with TG offset adjustments applied. Blue: Difference of TG (adjusted for storm surge, common mode signal and datum steps) and average of nearest 55 altimetry grid cells.

4.6.4. Revised MSL for the British Isles. We now construct the Final Common Mode (FCM) from the time series after correction for steps, this time retaining both linear and quadratic trends. Simple averaging presents a problem as offsets between series exist (each series is not referenced to the same absolute vertical datum) and they do not cover the same time period (Dangendorf et al. 2017). Any GIA errors will also cause apparent trend differences and introduce bias. The novel averaging process used here is to solve for all offsets in all time series simultaneously using weighted least squares in Matlab, accounting for data gaps and differing start and end times, but in this paper we do not attempt to account for GIA errors. We check this averaging is effectively identical to an alternative process of ranking the time series in length order, and then starting with the longest and most complete, to sequentially add each new series to update an overall average. At each stage the offset between the current average and each new series is estimated by least squares differences and this offset is then subtracted before creating a new weighted average. In both cases the average at each point in the time series is weighted by the number of contributing gauges.

Fig. 4.19 shows all of the adjusted and offset time series overlaid. The amount of direct curve overlap is visually represented by optical density, with a median, 1st and 3rd quartile plotted. The common mode variability is clearly evident.

Subtracting the surge model data results in greatly reduced high frequency variability in the average MSL data, but makes little difference to the formal trend (using CATS processing to account for power law noise models, the formal uncertainty actually increases slightly as a result of reduced white noise permitting a better estimate of the low frequency noise, see Table 4.2).

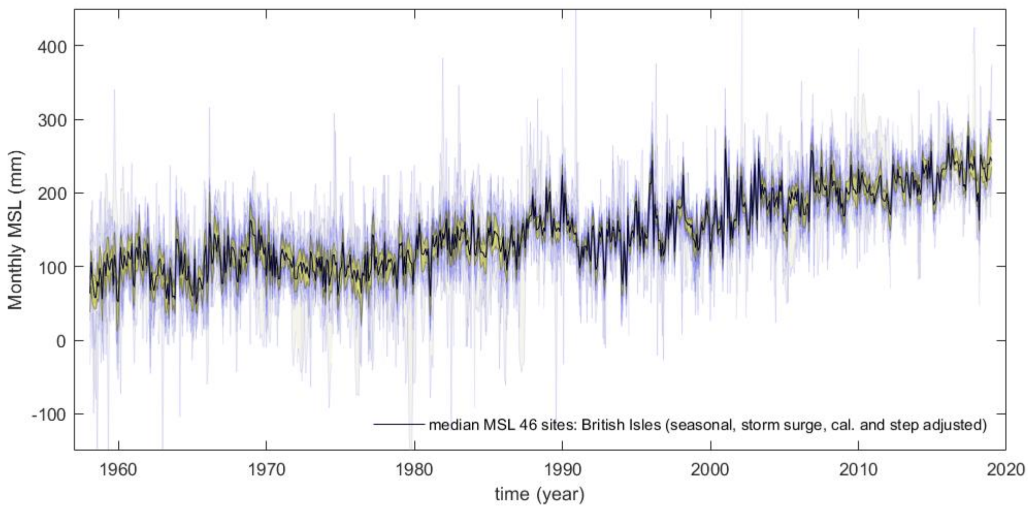


Figure 4.19: MSL all sites overlaid. Adjusted for GIA, seasonal effects, and local tide and storm surge, each series (blue in background) offset to weighted average signal. Median MSL from all sites (dark blue), 25th and 75th quartile limits (yellow) and light grey is max/min envelope of data from all sites including outliers.

Fig. 4.20 shows the variation in trend differences between the FCM and the MSL at each of the TG stations with more than 20 years of data. Each TG difference trend is estimated over the timespan of each TG record. Possible contributors to the residual trend differences include GIA model errors and VLM (see Fig. 4.22) as well as any remaining gauge errors.

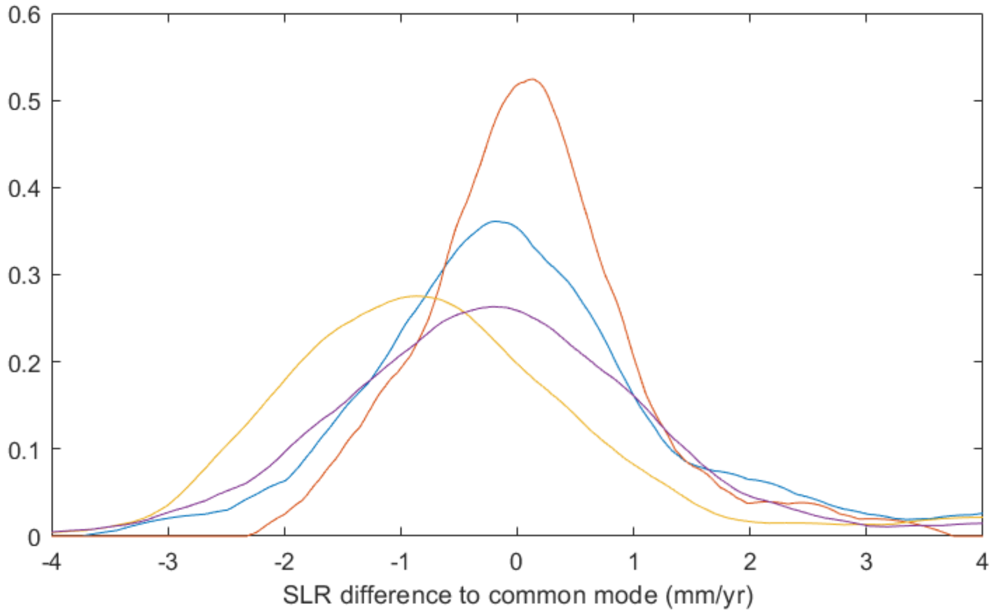


Figure 4.20: PDF of CATS derived trend of differences of deseasonalised MSL; all stations with >20 years of data minus the Final Common Mode signal from Fig. 4.19 (i.e. trends retained). This method accounts for variations in trend over different time periods due to the low frequency variability or acceleration. Red: GIA adjusted MSL, storm surge and offsets subtracted. Blue: GIA adjusted MSL with storm surge only removed. Purple: GIA adjusted MSL. Orange: MSL with no GIA adjustment.

4.6.5. Sea Level Acceleration. The question arises whether acceleration is detectable in the adjusted dataset. The minimum record length required in order to attempt separation of interdecadal ocean fluctuations from a long term acceleration signal in tide gauge data is much longer than the 20 years used here for SLR (Douglas 1992). In Fig. 4.21, a probability density function of CATS derived acceleration values is plotted using all 24 gauges with at least 50 years of data (at least 75% complete). This shows a median acceleration of around 0.05 mm yr^{-2} over the Jan. 1958 to Dec. 2018 period, and a greatly reduced spread of values around a positive mean compared with unadjusted data, indicating an increased likelihood of a positive acceleration signal.

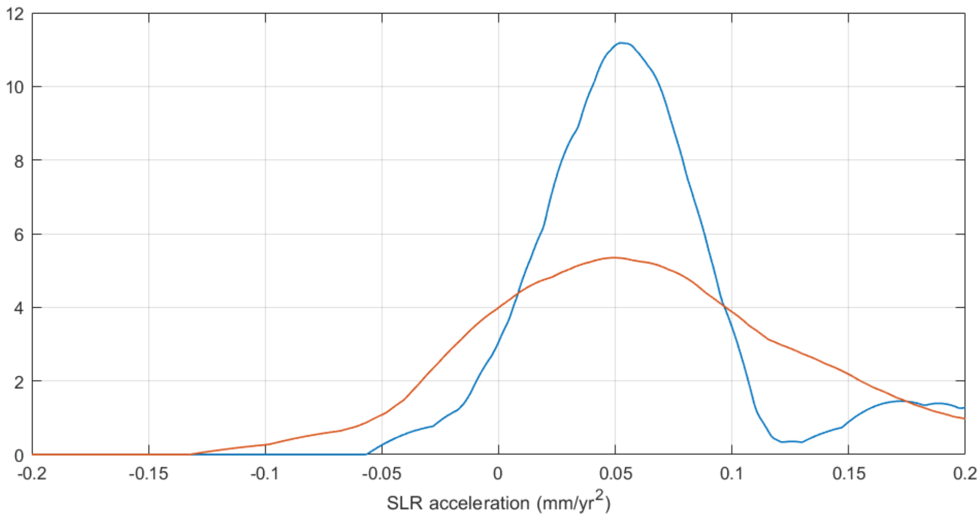


Figure 4.21: PDF of acceleration values for 24 sites with data having more than 50 years of data with 75% completeness. Blue: fully adjusted. Red: unadjusted (deseasonalised only) data, showing reduced spread of values once offsets are removed.

This illustrates the improved consistency of the tide gauge records once datum steps and local dynamics have been accounted for. However, similar time series will result in similar estimates of acceleration without that acceleration necessarily being statistically significant. To assess the accuracy of trends and accelerations, we apply the CATS analysis method to various Common Modes defined below (Table 4.2). The linear trends (SLR given by b) are derived accounting for a second order term (Williams et al. 2014) using (1).

$$y = a + b(t - t_0) + \frac{1}{2} c\,(t - t_0)^2 \qquad (1)$$

where y is sea level, a is a constant, b is the rate of rise, and c is the acceleration. We select t_0 so that b equals the derived trend in a linear fit over the full period Jan. 1958 to Dec. 2018, making b equivalent to the value which would be estimated with no acceleration term. This selection is done iteratively starting at the middle of the time series. This reduces the linear trend uncertainty in all cases considered here.

In order to test the robustness of our methodology, we also calculated three independent Common Modes based on tide gauges from the West, East and South coasts of the UK: FCMW, FCME and FCMS (similar to the method used for Fig. 9 in Woodworth et al. 1999). The FCM, and the differences between the local FCMs and the full FCM, are plotted in Fig. 4.22. The West coast here includes gauges from the Irish coast, and we also use four additional sites where the records have 75% completeness over a minimum 20 years, to maximise the sample number. These independent constructions, plus other tests such as using (or omitting) the small number of tide gauges with long and almost complete records, or constructing the FCM ignoring all "free floating" data segments (not shown), demonstrate the robustness of the FCM and of the procedure for correcting steps. The residual small linear and second order trend differences (Fig. 4.22; orange, red, purple) are suggestive of VLM changes and this could be investigated in further work (e.g. using CGPS compared with GIA models, Bingley et al. 2001; Teferle et al. 2002; Santamaría-Gómez et al. 2017).

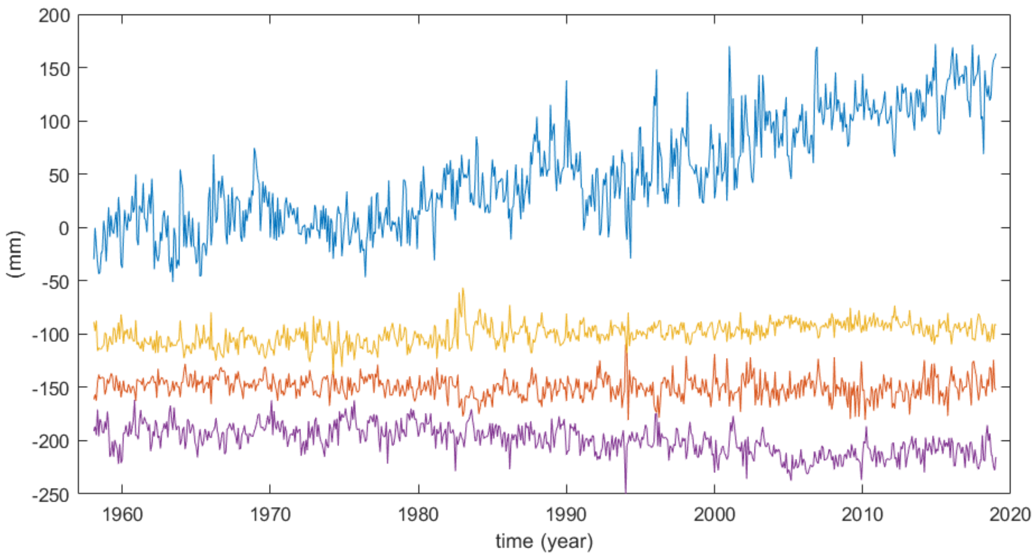


Figure 4.22: Top, Blue: Average monthly MSL signal for 46 sites around the British Isles after adjustment for GIA, seasonal variation, and local meteorological effects from a tide and surge model. This is the final "common mode" (FCM) signal with trends retained. Orange: West Coast Common Mode (21 sites) minus the average common mode. Red: East Coast Common Mode (16 sites) minus average. Purple: South Coast Common Mode (9 sites) minus average. The low frequency variations such as the 1988 excursion and sharp drop just after 1990 are robust features of the reanalysed MSL data. Series are offset to aid visualisation.

The resulting quadratic fit parameters and their errors are shown in Table 4.2, where the linear component should be interpreted as the rate in the middle of the period of analysis (start of 1988). We see that the average rate is around 2.4 mm yr^{-1} with around 10% error, and the acceleration is around 0.06 mm yr^{-2}, with around 50% error (without the correction for offset steps, and local dynamics, a slightly larger acceleration is seen). This latter error is dominated by the presence of low frequency variability in the FCM, as can be seen from the significantly smaller uncertainty in acceleration for the difference between the independent FCME and FCMW.

Data used for trend analysis	**SLR (mm/yr)**	**σ (mm/yr)**	**SLA (mm/yr^2)**	**σ (mm/yr^2)**
Average RLR MSL (34 sites)	1.92	0.23	0.085	0.026
Average MER MSL (46 sites)	2.22	0.23	0.077	0.027
ICM (Av. MER minus surge model)	2.30	0.28	0.066	0.030
FCM (Av. MER minus surge model & datum steps)	2.39	0.27	0.056	0.028
Av. MER: as above, 4 longest series only	2.39	0.36	0.049	0.038
FCME (E. Coast MER only) minus detrended FCM	2.21	0.05	0.073	0.006
FCMW (W. Coast MER only) minus detrended FCM	2.54	0.06	0.066	0.007
FCMS (S. Coast MER only) minus detrended FCM	1.89	0.10	0.054	0.011
FCME minus detrended FCMW	2.26	0.10	0.071	0.011
FCME minus detrended FCMS	2.20	0.12	0.070	0.011
FCMW minus detrended FCMS	2.47	0.16	0.065	0.017

Table 4.2: SLR and SLA trends derived from CATS, first two columns show linear trend and uncertainty. Third and fouth columns show the second order trend and uncertainty. Table also shows the impact of adjusting MSL series for surge model and different common mode signals prior to averaging. For example the reduction in variability after subtracting an independent "common mode" signal derived from all West coast site data and applying to each East coast site series before averaging shows an additional coherent underlying signal is present around the entire coastline which is not explained by the barotropic model.

4.6.6. Comparison with previous work. This revised estimate of regional MSL acceleration around the British Isles is comparable with our calculation of a CATS derived result from the global MSL reconstruction of Church and White (2011), (CW11, 2015 update) of 0.055 ± 0.013 mm yr^{-2} re-calculated for the 1958 to 2013 period. It is also close to both the global (1958-2015) and the subpolar North Atlantic accelerations for the slightly different period of 1968-2015 calculated by Dangendorf et al. (2019), which are 0.058 and 0.06 ± 0.01 mm yr^{-2} respectively. This is much higher than the figure of 0.013 ± 0.003 mm yr^{-2} estimated for the entire CW11 period since 1880, or the estimate of 0.011 mm yr^{-2} (Woodworth et al. 2009b) for the UK sea level acceleration over a similarly long period, although it is only marginally higher then the global CW11 acceleration for a more equivalent 55 year period centred on 1931. The global linear trend estimate (SLR) for updated CW11 for the period 1958 to 2013 is also comparable (2.17 ± 0.12 mm yr^{-1}, the uncertainty is again reduced if the second order term is also accounted for). There are good reasons, such as the influence of the Greenland Ice Sheet, why the acceleration might not match either the global or North Atlantic accelerations over multidecadal timescales, but we do not investigate this here.

If we wish to improve the estimate of acceleration, we must reduce the impact of this low frequency variability either by seeking longer time series (Hogarth 2014; Haigh et al. 2014), or by finding a physical cause (assuming that to be separable from the long term sea level rise), and subtracting it out.

4.6.7. Investigating causes of the common mode.

Our initial hypothesis was that we should expect a Common Mode to reflect the influence of ocean dynamics from beyond the continental shelf, as well as mean sea level rise. We test this by correlating the FCM with satellite altimetry everwhere (with seasonal signals and trends removed). The result, shown in Fig. 4.23, clearly shows that the FCM is related to eastern boundary Atlantic dynamics, which have previously been attributed to the response to longshore wind stress integrated from the equator (Calafat et al., 2012; 2013). The link to the basinwide Greenland-Iceland-Norwegian (GIN) sea response further north is consistent with the same effect exciting a pan-Arctic sea level oscillation, the mechanism for which has been elucidated by Fukumori et al. (2015). Thus, if we wish to explain the FCM, a response to longshore winds would be the first place to look. We intend to explore this issue further in future work, and also consider other contributing factors such as steric variations (Roberts et al. 2016). Promising correlations are also seen with sea surface temperature over the entire 60-year period, over a wide region (not shown).

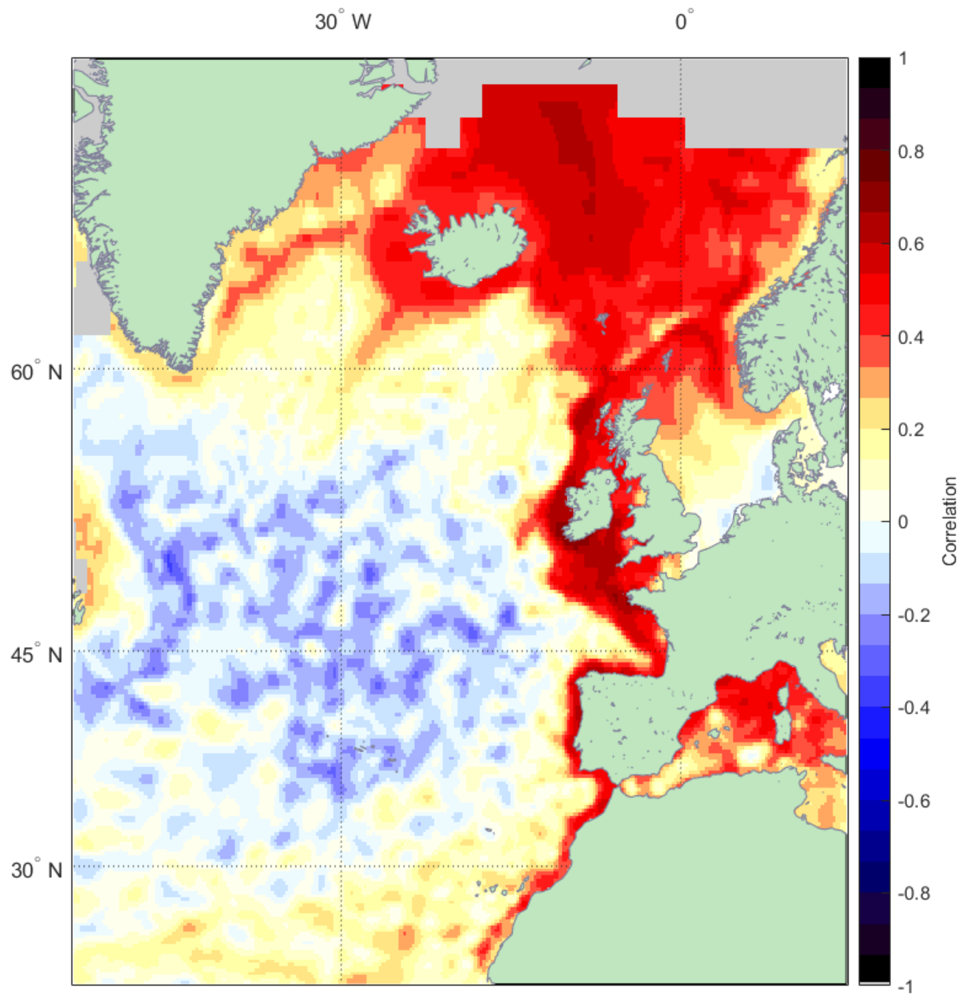


Figure 4.23: Correlation of detrended final common mode signal (FCM, average of MSL around the British Isles after offsets, storm surge model data and seasonal components are removed) with detrended and deseasonalised satellite altimetry data. This pattern is robust even if only tide gauge data from the UK east coast is used to create the common mode signal.

It is worth noting that a very similar correlation pattern emerges if we use the FCME, based on the UK east coast, despite the fact that the altimetry correlations along the east coast are low. This is presumably because the local dynamics have not been subtracted from the altimetry here, and these contain a component which is anticorrelated with the FCM on the east coast.

4.7. Summary and conclusion

Removing local dynamical effects from British Isles tide gauge measurements based on a barotropic, local shelf sea model, and then constructing a "Common Mode" by averaging the residual signals and removing that, has permitted us to identify a number of previously unrecognised steps in the tide gauge record.

In response to this, an intensive data archaeology exercise has allowed:

- Extension of existing tide gauge datasets using archived bench mark and datum information.
- Collation and digitisation of metadata detailing instrumentation changes at each site.
- Centimetre scale corrections to a number of site datum connections from archived tide gauge calibration data.

These extended and corrected datasets have further allowed:

- Confirmation that most of the steps coincide with recorded instrumentation changes.
- A correction for the steps which in most cases is based on documented levelling measurements.
- Consequent reduction in low frequency variability at many individual sites.
- Reduced variance between site data, with coherent interannual patterns at local scale.
- Increased correlation of rates and accelerations of sea level rise at all sites.

The effect of estimating and removing the tide gauge zero offset steps is to both increase the overall correlation between data from all sites and to reduce the variability at each site. A large number of the newly adjusted time series now appear similar to each other and to time series from the handful of sites where the RLR data was previously assessed as high quality (such as Lowestoft or Newlyn). The correlation between MSL trends adjusted using a GIA model at different sites as well as between Altimeter and TG MSL records and trends is also improved. These results do not substantially alter the SLR picture obtained previously using selected RLR PSMSL data, but they do greatly increase confidence in the conclusions, and allow problematic sites to be identified or even rehabilitated more easily.

The new average MSL signal is similar in concept to the longer-term UK "Sea Level Index", (Woodworth et al. 2009a) after the tide and storm surge (meteorological) variability and datum steps have been removed (Fig. 4.22, top trace). This Final Common Mode variability shows a mean sea level rise of 2.39±0.27 mm yr^{-1}, and an acceleration of 0.058±0.030 mm

yr^{-2} between the start of 1958 and the end of 2018 (N.B. the linear rates are corrected for GIA using the ICE-6G_C (VM5a) model as described in the data section above). The central estimate implies a rate rising from 0.33 mm yr^{-1} at the start of the record to 4.11 mm yr^{-1} by the end, with an average rate over the satellite altimetry period (start of 1993 to the end of 2017) of 3.46 mm yr^{-1}. This is consistent with the recently reported global acceleration over the altimetry era of 0.084±0.029 mm yr^{-2} (Nerem et al. 2018), and much stronger than the typical 0.01 mm yr^{-2} acceleration observed over century time scales (Hogarth 2014).

Comparison with satellite altimetry (Fig. 4.23) shows that the Common Mode is linked to eastern Atlantic boundary variability. It may be possible to reduce error bounds on the underlying acceleration if a model for the wind-driven component of these boundary signals can be used to reduce the interannual to decadal variability seen in the Common Mode.

This reassessment and improved consistency of the tide gauge records relied heavily on the existence of redundant tide gauge measurements and of levelling information which constrains the "free floating" segments of the records. Many of the steps we detected are subsequently reversed as later levelling reasserts the correct datum following some earlier equipment change. In this context, the recent drop off in the number of usable tide gauge records and in levelling to nearby datums (Fig. 15) is alarming as, without this combination of redundancy and levelling, the quality of reconstruction of the common mode is likely to degrade into the future, limiting our ability to detect future accelerations.

It is also pertinent to assess data from some of the recently installed radar tide gauges which are not covered in this analysis (as they have been running less than 20 years). An initial examination of some of the longer radar gauge records indicates that despite the intrinsic stability of such gauges (Woodworth and Smith 2003) unrecorded datum changes are still evident. For example, for the almost continuous 2006 to 2018 record from Deal Pier (approx. 15km N.E. of Dover) two datum steps of around -40mm are identified at mid-2011 and the end of 2013 by the buddy check and model difference methods. These lead to an uncorrected (and clearly erroneous) trend of -7.9 mm yr^{-1}, whilst the adjusted trend after the processing steps outlined here gives 2.2mm yr^{-1}. Unfortunately, no physical changes are recorded in the available site documentation.

A broader implication of this work is that additional levels of quality control should be considered before drawing conclusions about SLR from regions where only small numbers of gauges are available.

4.8. Data Availability

A processed data set and associated metadata is available online through Zenodo at: doi.org/10.5281/zenodo.3747196

The data is available in .csv spreadsheet format and also as MATLAB® .mat format files, the .mat files are simple 2-D data arrays where columns 1 to 1351 correspond to the PSMSL site id. number, and rows 1 to 3228 correspond to months from Jan. 1750 to Dec. 2018.

Acknowledgements:

This paper contains work conducted during a PhD study supported by the Natural Environment Research Council (NERC) EAO Doctoral Training Partnership and is fully-funded by NERC whose support is gratefully acknowledged. Grant ref no is NE/L002469/1, UKRI award ref 1950000.

The authors declare that they have no conflicts of interest.

All code used in this research was developed using MATLAB® release 2019a.
MATLAB® is a registered trademark of The MathWorks, Inc., Natick, Massachusetts, United States

Thanks to: P. L. Woodworth for useful comments on earlier versions. The authors also thank the three reviewers whose comments have further improved the paper. We also acknowledge the many contributors to on-line MATLAB® forums who have provided inspiration for more efficient coding solutions. Maps in MATLAB® were created using:

Pawlowicz, R. (2019). "M_Map: A mapping package for MATLAB", version 1.4k, [Computer software], available online at www.eoas.ubc.ca/~rich/map.html.

Peter Kovesi. Good Colour Maps: How to Design Them.
arXiv:1509.03700 [cs.GR] 2015

Chapter 5. Case study: MSL for the waters around the British Isles since 1813

Context of the paper in relation to the thesis

This paper, which forms chapter 4, addresses the second main research aim of the thesis given in the introduction, using data archaeology to extend sea level records wherever possible. A large amount of historical sea level data exists which has yet to be adjusted to a known land survey based reference level so that it can be compared with modern records. This again is an issue of datum continuity. This paper uses the methods outlined in Chapter 4 as well as the results of a data archaeology exercise, taking the important step of using historical levelling data to connect sites along a localised section of coastline. This allows geodetic connection between old and new data within predictable uncertainty levels. This then allows even short records to be assimilated. In addition, the results of the least squares averaging method described in chapter 4 are shown to reduce large inter-site level differences allowing a single composite UK record to be developed. This is important in the context of this thesis and also for global studies, as it addresses some of the issues previously identified when attempting to derive a global mean sea level curve from records which have incomplete temporal and geographical coverage. The final composite record clearly shows sea level rise and acceleration over the industrial period, thus addressing the fundamental research question of whether acceleration is discernible, for the UK Coastline at least.

This work has been published as: Hogarth, P., D. T. Pugh, C. W. Hughes and S. D. P. Williams, 2021: Changes in mean sea level around Great Britain over the past 200 years. *Progress in Oceanography* **192**, 102521, doi: 10.1016/j.pocean.2021.102521.

As lead author I led the research, compiled, digitised, checked and interpreted the data, wrote the paper, generated the MATLAB code, plots and tables and managed the publication process. David Pugh discovered the Admiralty Ledgers and we both independently digitised the data. My supervisors Chris Hughes and Simon Williams provided valuable supervision, and suggestions for analysis methods, as well as a vertical land motion dataset (SDPW). All co-authors provided editorial critique, and discussion of ideas.

Permission to include this paper in the thesis is given by all three co-authors:

David T. Pugh:

Chris W. Hughes:

Simon D. P. Williams:

SDPWilliams

"Changes in Mean Sea level around Great Britain over the past 200 years"

based on data from 1813 to 2018

Hogarth, P.[1,2], Pugh, D. T.[1], Hughes, C. W.[1,2], Williams, S. D. P.[1]

([1,] National Oceanography Centre, Liverpool, L3 5DA, United Kingdom, [2,] University of Liverpool, Liverpool, L69 3BX, United Kingdom)

Corresponding author: Peter Hogarth (pehoga@noc.ac.uk)Peter Hogarth, Floor 1, NOC, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA

Key words: sea level rise; sea level acceleration; mean sea level; tide gauge; data archaeology

Abstract

We systematically assimilate a wide range of historical sea level data from around the coast of Great Britain, much of it previously unpublished, into a single comprehensive framework. We show that this greatly increased dataset allows the construction of a robust and extended Mean Sea Level curve for Great Britain covering a period of more than two centuries, and confirms that the 19th century trend was much weaker than that in the 20th century and beyond. As well as attempting to maximise the amount of newly recovered sea level observations, we have also recovered the levelling metadata necessary to connect this 19th and early 20th century data with modern records. We adjust this data for known sources of variability and estimate overall uncertainties over the entire period. Data are processed in 36 regional clusters, before recombining to compute national statistics. We investigate the advantages of extending and adjusting the time series on sea level rise trends and low order variability. Confidence limits are improved by better than 60%. The weighted linear trend since 1900 for the fully adjusted data points from all clusters when averaged annually and adjusted for Glacial Isostatic Adjustment is 2.12 mm/year ± 0.02 mm/year (1-sigma). The much lower trend estimated for the 19th Century alone is 0.24 ± 0.12 mm/yr. There is an acceleration of 0.012 mm/yr^2 ± 0.003 mm/yr^2 in the rate of rise over the period 1813 to 2018. These trends are quite sensitive to the GIA correction used, but their differences and accelerations are not.

5.1. Introduction

The observational evidence thus far suggests that UK sea level rise (SLR) was low during the latter third of the 19th Century (Woodworth et al. 1999, Woodworth 2018), followed by a change in slope leading to about 1.4 mm/yr average rate of rise through the 20th century (Woodworth et al. 2009), and an accelerating rate averaging 2.39 mm/yr since 1958 (Hogarth et al. 2020). This is consistent with a small number of European gauges with long records (Brest, Cuxhaven, Amsterdam/Den Helder; Woodworth 2018). However, these conclusions are mainly based on the UK continuous tide gauge record which is limited prior to about 1954, and before the 20th century is dependent on a very small number of gauges with discontinuous temporal coverage.

Woodworth (2018) showed that short tide gauge records with good datum control from the First Geodetic Levelling of the UK by the Ordnance Survey in 1858-59 when differenced with nearby modern measurements, could give valuable information on the mean trends over that interval, which was generally supportive of the above interpretation. A number of suggestions were made about how to exploit such information further.

In parallel, Hogarth et al. (2020, Chapter 4 of this thesis) performed a data archaeology exercise which led to improved datum control and extension of a large number of UK records, and established that the records could be considered to consist of a seasonal cycle, a component driven by local atmospheric forcing, a linear trend associated with GIA, and a Common Mode which is uniform around the UK, as well as small residual local sea level variations.

In this study we use the same techniques as Hogarth et al. (2020) to extend and improve the Permanent Service for Mean Sea Level (PSMSL) dataset (Holgate et al. 2013) before 1958, and undertake a further extensive data archaeology exercise in order to greatly expand the sources of early data in the style of Woodworth (2018). We introduce a large number of early, short duration records associated mainly with Admiralty surveys, many of which have not been previously accessed. We then partition this data into 36 localised clusters around the UK, enabling us to extend and densify the early UK instrumental sea level record, confirming the low trend in that early period, and providing more robust measures of the time series back to the early 19th century. All data used is derived from at least daily observations (usually high and low waters) averaged over periods of at least a fortnight (semi-lunation). We use the following terminology:

“Continuous” data refers to time series of annual averages of monthly mean data from long term sea level monitoring sites, as traditionally used by the PSMSL.

“Campaign” data refers to sea level averaged over shorter term survey periods, from portable tide gauges levelled in to fixed land based reference points such as bench marks. These include episodic surveys carried out by the Admiralty, the coverage of which can range from two weeks to over a year, and the series of observations by the Ordnance Survey (OS) during the 19th Century.

“Newly assimilated” data means all of the campaign data (including the OS data used by Woodworth 2018), plus any continuous data that has been made usable by newly-recovered datum control information. The latter, in the manner of Hogarth et al. (2020) allows the formation of an extended version of the PSMSL RLR dataset which is referred to here as the Metric Extended Reduced (MER) record.

A particularly important source of information for this study came from the UK Admiralty archives in the form of the Admiralty Tidal Ledgers and Admiralty Datum Ledgers kept at the UK Hydrographic Office in Taunton, which contain detailed information on a range of sea level measurements and the associated datums.

In brief, the sources of newly assimilated sea level data (equivalent of 3348 station months) used in this paper are:

1. Continuous observations from fixed gauges at Naval Dockyards at Sheerness, Plymouth, Portsmouth and Pembroke. Annual means for several years are derived from twice daily HW and LW readings between 1832 and 1834, or for Sheerness, 1832 to 1843 and 1870 to 1894.
2. Campaign data from Admiralty sources such as the Tidal Ledger (supplement 2), covering 168 sites from 1834 to the 1950s; data published by the International Hydrographic Bureau (IHB; now the International Hydrographic Organization), and data included on Admiralty Charts. Time spans range from 2 week surveys using portable tide gauges to segments of over a year extracted from longer records which existed at the time.
3. OS campaign data (19 sites from 1859 with spans of around two weeks, and 13 other sites with earlier dates, plus sites from 1896) these are covered in detail in Woodworth (2018).

4. Continuous data from “permanent” gauges published in various historical documents which has not yet been assimilated into the PSMSL records.
5. Short term campaign data from civil engineering, scientific, and harbour surveys.
6. 21st Century data from nine recently installed tide gauges not currently included in the PSMSL, including Blyth, Buckie, Cromarty, Inverness, Oban, Scarborough, Shoreham, Stranraer and an additional gauge at Whitby. These aid comparison with early data from these sites.
7. Unpublished data and metadata recovered from the National Oceanography Centre (NOC) archives in Liverpool (PSMSL and British Oceanographic Data Centre (BODC) archives).

By spatially clustering these new data sources, the temporal span of data available at almost all 36 clusters now exceeds a century. Overall an extra 1635 station-months or 136.25 equivalent station-year datapoints are added prior to 1900; 833 station-months or 68.7 station-years of these are prior to 1858. These include multi-year records in the 1830s from the four Naval Dockyards at Sheerness, Portsmouth, Plymouth and Pembroke Dock.

Sea level relative to local land based reference points (RSL) as recorded by a perfect (i.e. one only influenced by changes in relative sea level) tide gauge (TG) is influenced by a combination of factors including local tide and meteorological effects, distant ocean variability and vertical land motion (Rossiter 1967, Thompson 1980, 1981). Tide gauges (and observers) are however imperfect, and this results in additional variability in the TG records caused by discontinuities in recording methods (e.g. changes from daylight only to 24 hour observations) (Woodworth 2016) or instrumentation or datum control errors (Lennon 1971), causing false level changes or steps in the record, (Haigh et al. 2009). This last factor has been shown to be a significant source of low frequency variability, requiring correction even in modern data (Hogarth et al. 2020). Adjusting for these factors results in more consistent RSL records. Considering the UK sea level data from 1958 to 2018, the impact of any individual residual gauge error can be reduced by averaging simultaneous observations from a number N of different sites, by a factor of 1/sqrt(N). Extending the time series is also important as errors in linear trend due to a step-like datum error of given magnitude will reduce as the record length increases, the relationship approximating an inverse power law. Whilst this paper focuses on extending the dataset for the British Isles, a region in Northern Europe where there are already a high proportion of long time series, the methodology may prove useful for other regions which are poorly represented in the existing PSMSL dataset. The data archaeology has already revealed archived data from many global sites which has not yet been digitised and assimilated.

Tide gauge data are often reported relative to a national datum; a nominally level surface, determined by levelling between sites. It is now known (Penna et al. 2013) that this is prone to decimetre-scale errors at the scale of Great Britain (GB), and the periodic relevelling exercises and changes of chosen reference will introduce artificial time dependence in the sea level record. However, levelling over shorter distances is much more reliable, as shown below, and probably not the major error source. Accordingly, we initially group the measurements into 36 local clusters (this is somewhat arbitrary, but clusters are defined by proximity and, where possible, geodetic connection during local scale levelling, avoiding levelling across large estuaries), within which we consider levelling errors to be small, so that sea levels can be directly compared from site to site and subsequently combined in optimal ways. These clusters are further refined in the light of data analysis, see Fig 5.10). A significant component of the work presented here is the correct identification of the relationship between the reported reference level of sea level data, and local benchmarks, so that all can be considered relative to a modern, consistent datum.

Sections (5.2) and (5.3) of this paper cover the sources of data used: (5.2) gives the sources for currently available Mean Sea Level (MSL) and the data required for adjusting the MSL records, and then (5.3) gives details of the sources and availability of the newly assimilated sea level measurements from the early 19th Century onwards around the coast of GB. Section (5.4) describes the data processing including adjustments and quality control checks, and discusses the uncertainties. The data is then partitioned into localised clusters, each around a central station for which recent MSL data are held by the PSMSL. All adjusted values within a cluster are treated as a set, and trends within each cluster are computed independent of other clusters. Table S5.4 in the appendix summarises the useable data sources, adjustments and uncertainties. Section (5.5) describes the results of the analysis. We then estimate the vertical offsets between different clusters by comparing the modern fully adjusted PSMSL (MER) records, and then apply these offset values to all older data within each cluster. This allows an overall annual average MSL for the British Isles to be estimated over a 200 year period. Section (5.6) discusses these results and quantifies how the additional data provides independent confirmation of sea-level rise acceleration, briefly considering adjustments for vertical post-glacial crustal movements and Section (5.7) concludes and discusses directions for further work.

5.2. Data sources

The sources of information considered for this paper are restricted to GB (England, Scotland, Wales and some island sites). Similar studies could be undertaken for other countries, notably Ireland for which many of the sources are identical.

5.2.1. Existing Sea Level data

The PSMSL is the main global data repository for continuous MSL time series (Holgate et al. 2013), https://www.psmsl.org/data/. The PSMSL datasets are available as “Metric” (monthly means only), regularly updated by national monitoring authorities around the world, and Revised Local Reference (RLR, monthly and annual means) based on the Metric data, but with quality control applied by the PSMSL as far as possible. The Metric data is usually referenced to the elevation of the tide gauge zero (TGZ), which may be altered occasionally, for example as instruments were replaced. For many sites, the PSMSL have records of these TGZ elevation changes relative to fixed “permanent” bench marks. This allows the sea level data to be referenced to a consistent land-based datum as part of the quality control, which the PSMSL define as “RLR”. In the UK the RLR elevation is also linked through bench marks to local values of the National levelling datum, Ordnance Datum Newlyn (ODN), based on the MSL at Newlyn between 1915 and 1921 (Bradshaw et al. 2016), and usually to the Admiralty Chart Datum (ACD) which is based on some definition of local low water relative to ODN as used for Nautical Charts. Whilst the PSMSL holds some examples of 19th and early 20th Century RLR data from sites such as Liverpool and Sheerness, recovered retrospectively after the Service was set up in 1933 (IAPO 1939, 1958), the number of sites with long records suitable for trend analysis is limited (see Fig. 5.5 for locations with more than 40 years of PSMSL data). Around 15 recording gauges were operating in 1911 (Henrici 1911), and only 9 permanent tidal observatories were recorded around the GB coastline in 1902 (SOI 1905). Only five of the GB PSMSL RLR series contain more than 100 years of data with more than 75% completeness: Newlyn, North Shields, Aberdeen, Liverpool and Sheerness. The Sheerness PSMSL RLR series has the longest span, but several gaps. The Aberdeen, Liverpool, and North Shields series are effectively composite series using close but not exactly co-located sites. Three RLR sites have data from prior to 1895, two prior to 1862, and only one has data (Sheerness, 15 station-years) prior to 1858.

To maximise record length, we consider Metric data from the PSMSL from the earliest date available at each site up to the end of 2018. For example the Metric dataset contains additional published 19th Century monthly Mean Tidal Level (MTL; the average of high and low tides) for Holyhead, (Beechey 1848), and Milford Haven and Dundee (Thompson 1914). We are now able to adjust much of this data so that it is referenced to local ODN using newly recovered datum offset values, effectively applying RLR style adjustments. This is an extension of the work described in Hogarth et al. (2020) using only slightly modified methods to recover and adjust information before 1958. The limited number of extended annual results are added to the "newly assimilated" data (section 5.3).

5.2.2. Meteorological data

One-degree gridded monthly and daily mean sea level pressure (MSLP) and u and v wind components from 20CRv3 (Slivinski et al. 2019) were downloaded from: https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV3.monolevel.html

Five-degree gridded monthly MSLP (Luterbacher et al., 2002) for the Eastern North Atlantic and Europe (ASCII: slp_1659-1999.txt) was downloaded from: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/historical/north_atlantic.

5.2.3. GIA model data

The Peltier ICE-6G_C (VM5a) GIA model data (Peltier et al. 2015; Argus et al. 2014) for all PSMSL sites was downloaded from http://www.atmosp.physics.utoronto.ca/~peltier/data.php. The correction we apply includes gravitational effects due to the changing ice mass loads on the solid Earth since deglaciation and the resulting modifications to the gravity field as well as vertical land movement, removing the secular component of RSL that results from GIA. For sites not in the PSMSL we interpolate the 0.2 degree gridded GIA dataset dsea.12mgrid.nc also available from http://www.atmosp.physics.utoronto.ca/~peltier/data.php. We also checked agreement between grid derived values and those given for the PSMSL sites.

5.3. Newly assimilated sea level data

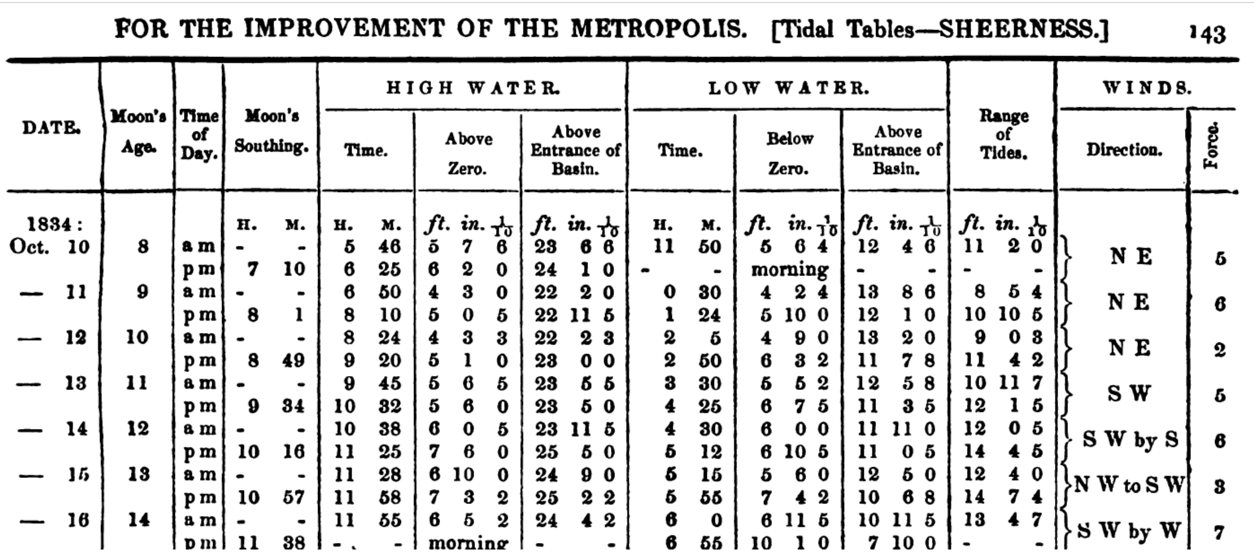
Improvements were made to the PSMSL data holdings by using the methods described in Hogarth et al. (2020), where the datum levels for additional Metric data as well as datum step errors have been systematically identified and resolved wherever possible. This MER dataset shows reduced variability for post 1958 PSMSL data, but here the results are extended over the entire observation period at each site, and such extensions are considered as 'new' data, for example we have recovered the 19th C datum information for Holyhead (Hawkshaw 1873; Thomson et al. 1879) as well as Neyland (Milford Haven) and

Dundee (Thompson 1915), allowing this data to be included. Details of the new data, metadata and various adjustments are summarised in Table S5.4.

5.3.1. Admiralty dockyards

Lloyd (1831) gives details of setting up and levelling a tide gauge at the Admiralty dockyard at Sheerness in the lower Thames Estuary in March 1830. Lloyd's gauge registered HW and LW only, but was modified by Mitchell the Dock Engineer so that by September 1831 it was self-registering (Anon, 1832), on similar principles to the gauge proposed earlier that year by Palmer (1831). Lloyd also gives mean annual levels for high water and low water for 1827, 1828 and 1829 as well as monthly MTL for 1827 read manually from the tide scale carved on the stone of the dock caisson. The zero reference of this scale was the level of the paved entrance of the dock. Lloyd used the 31 foot mark on the same scale to give a tidal reference point and connected this to several bench marks he set up (Bevans 1832) (e.g. http://www.bench-marks.org.uk/bm27754). Some of these still exist and were later re-levelled by the OS. The tide gauge zero was set to "18 feet" above the dock entrance. This was actually 17 feet and 11 inches in the hand written tidal register of HW and LW (Bradshaw et al. 2015), which was close to the observed MTL (see below). Thus the recorded sea level and the original stone tide scale zero can be connected to the modern ODN.

The Admiralty also installed similar automatic gauges at other Dockyards: Portsmouth, Plymouth (Walker 1846) and Pembroke. In addition to the original mareogram records, each HW and LW (night and day) was manually recorded in tidal ledgers, the values usually read directly from the tide gauge record, or occasionally from a tide pole when the automatic gauge was non-operational. Tables of these twice daily HW and LW were published by the Royal Society (Admiralty, 1833) and the Admiralty (Anon, 1835). Until now, this data has not been systematically analysed. The original tabulated data, 1832-34, is held in the Royal Society library, and in the Admiralty Library in Portsmouth Dockyard. Tabulated daily measurements from Sheerness for the extended period 1832 to 1843 were also published in the report of the Metropolis Improvement Commissioners (Anon 1845). These were also referred to the entrance of the dock as well as the TGZ, which resolves any ambiguity about the gauge zero setting over this period (Fig. 5.1)



FOR THE IMPROVEMENT OF THE METROPOLIS. [Tidal Tables—SHEERNESS.] 143

DATE.	Moon's Age.	Time of Day.	Moon's Southing.	HIGH WATER. Time.	HIGH WATER. Above Zero.	HIGH WATER. Above Entrance of Basin.	LOW WATER. Time.	LOW WATER. Below Zero.	LOW WATER. Above Entrance of Basin.	Range of Tides.	WINDS. Direction.	WINDS. Force.
1834:			H. M.	H. M.	ft. in. 1/10	ft. in. 1/10	H. M.	ft. in. 1/10	ft. in. 1/10	ft. in. 1/10		
Oct. 10	8	a m	- -	5 46	5 7 6	23 6 6	11 50	5 6 4	12 4 6	11 2 0	N E	5
		p m	7 10	6 25	6 2 0	24 1 0	- -	morning	- -	- -		
— 11	9	a m	- -	6 50	4 3 0	22 2 0	0 30	4 2 4	13 8 6	8 5 4	N E	6
		p m	8 1	8 10	5 0 5	22 11 5	1 24	5 10 0	12 1 0	10 10 5		
— 12	10	a m	- -	8 24	4 3 3	22 2 3	2 5	4 9 0	13 2 0	9 0 3	N E	2
		p m	8 49	9 20	5 1 0	23 0 0	2 50	6 3 2	11 7 8	11 4 2		
— 13	11	a m	- -	9 45	5 6 5	23 5 5	3 30	5 5 2	12 5 8	10 11 7	S W	5
		p m	9 34	10 32	5 6 0	23 5 0	4 25	6 7 5	11 3 5	12 1 5		
— 14	12	a m	- -	10 38	6 0 5	23 11 5	4 30	6 0 0	11 11 0	12 0 5	S W by S	6
		p m	10 16	11 25	7 6 0	25 5 0	5 12	6 10 5	11 0 5	14 4 5		
— 15	13	a m	- -	11 28	6 10 0	24 9 0	5 15	5 6 0	12 5 0	12 4 0	N W to S W	3
		p m	10 57	11 58	7 3 2	25 2 2	5 55	7 4 2	10 6 8	14 7 4		
— 16	14	a m	- -	11 55	6 5 2	24 4 2	6 0	6 11 5	10 11 5	13 4 7	S W by W	7
		p m	11 38	- -	morning	- -	6 55	10 1 0	7 10 0	- -		

Figure 5.1. An extract of the tabulations for Sheerness: high and low water times and heights, wind direction and force.

The details of these twice daily measurements, which record the times and heights of high and low waters, are summarised in Table 5.1.

Dockyard	Latitude (degrees N)	Longitude (degrees E)	Start	End (inclusive)	Resolution
Sheerness	51.446	0.743	Jan 1832	Dec 1843	0.1 inches
Sheerness			Jan 1870	Oct 1894	1.0 inches
Sheerness			Jan 1930	Dec 1930	1.0 inches
Portsmouth	50.802	-1.111	Jun 1832	Dec 1834	0.1 inches
Plymouth	50.368	-4.185	Jun 1832	Dec 1834	0.25 inches
Pembroke Dock	51.692	-4.944	Nov 1832	Dec 1834	1.0 inches

Table 5.1: summary of available data from four Admiralty dockyards. 1 inch = 25.4 mm.

The MTL values we derive here are computed independently by digitising these original tidal ledgers. For Sheerness, this gives us several years over which we can directly compare MTL to existing MSL records. We can then use this information to fill some of the large gaps in the coverage of the current MSL series with additional monthly data from various sources, for example we have also digitised the daily tidal ledgers from Sheerness (HW and LW) from 1870 to 1894 (this may be duplicating earlier work; Rossiter (1972) plots some annual values, hand written versions of which we have found in the archives), and the ledger containing a year of daily data from 1930 (scanned images of these original hand written ledger pages recently made available from the BODC). We have also digitised around a month of HW and LW measurements from Sheerness from 1856 (Redman 1877b), as well as some data from 1952. We have also added the manually recorded monthly MTL data (calculated from daytime only observations at the same dock caisson tide scale used by Lloyd) from 1827 (Lloyd 1831) in order to create a more complete monthly time series. The annual average (or seasonally adjusted and weighted average of sections shorter than 12 months) of this new monthly dataset is used to create an extended annual time series for Sheerness. This is further extended with addition of old published annual mean values, derived from original records which may no longer exist (e.g. (Lloyd 1831) gives annual values for Sheerness for 1828 and 1829).

In summary we have digitised all the tabulated HW and LW data for the periods in Table 5.1 as well as available data from historically published analyses. This involved more than 136,000 spreadsheet entries. Most entries were transcribed independently by the first two authors, then compared. The handful of individual discrepancies were then investigated and resolved. Each time series was also checked visually, which allowed us to resolve a small number of 19th Century transcription errors.

The Portsmouth, Plymouth and Pembroke Dock daily measurements were also recorded at least to 1838 and results were published by the Admiralty (1839). These were cited in the First Geodetic Levelling (FGL) report of the Ordnance Survey (James 1861a). To date no copy of these observations has been found, but the OS report does give MTL values averaged over the four years 1835 to 1838 for these three sites (James, 1861a). In addition, for Plymouth, tables of annual MHW and MLW for 1833 to 1838 as well as annual mean levels were published (Whewell 1839) derived from these original records.

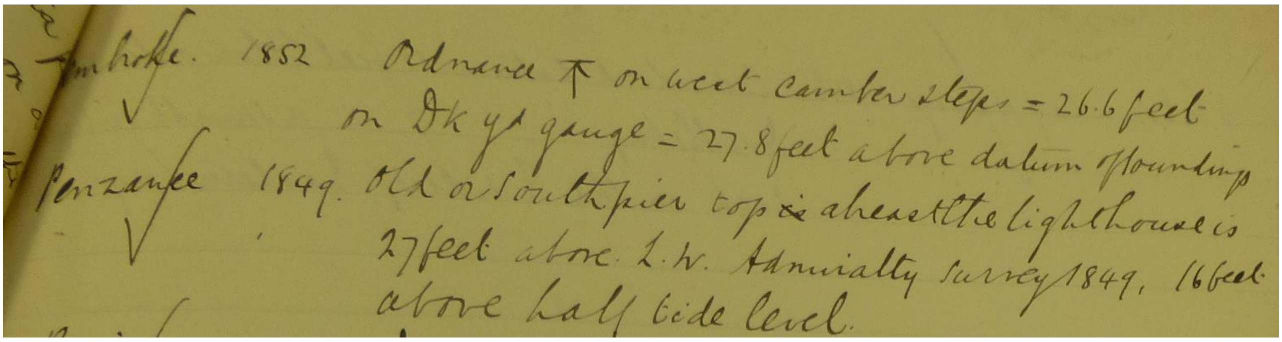

Pembroke. 1852 Ordnance ⤒ on west camber steps = 26.6 feet
on Dk yd gauge = 27.8 feet above datum of soundings
Penzance 1849. Old or South pier top is abreast the lighthouse is
27 feet above L.W. Admiralty Survey 1849, 16 feet
above half tide level.

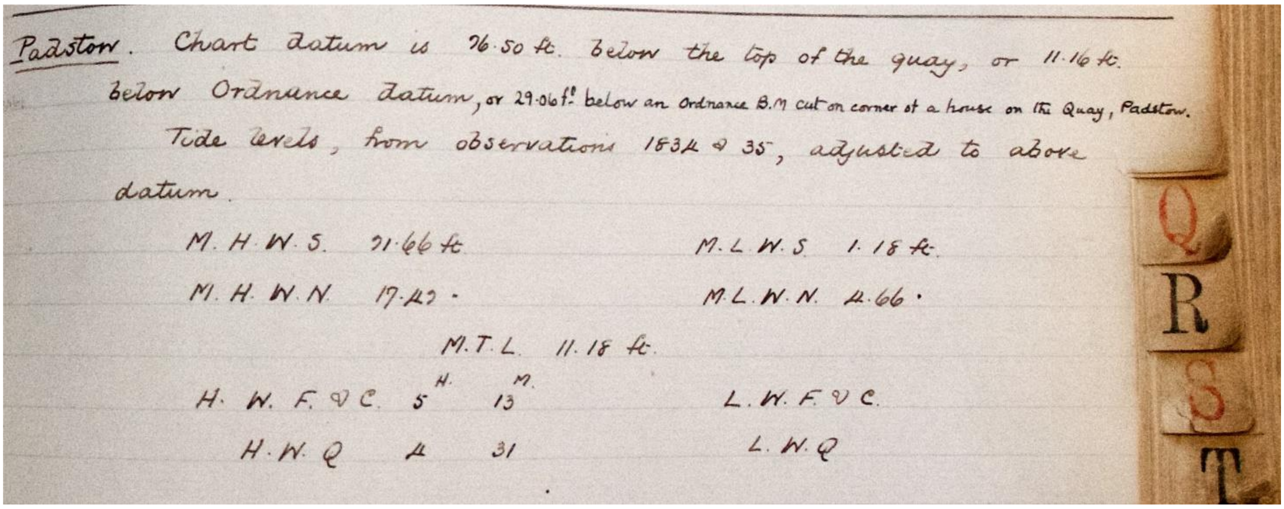
Figure 5.2: extract from the Tidal Ledger Volume 1, showing the earliest entry for Pembroke Dock (top). "Pembroke. 1852 Ordnance ⤒ on west camber step = 22.6 feet on Dock Yard gauge = 27.8 feet above datum of soundings" (depth on charts). The arrow and bar symbol refers to a bench mark, in this case set by the OS in 1841. There are several updates for

Pembroke later in the Ledger. This information should be used in conjunction with the date of the tidal observations in order to ensure the correct tide gauge zero and bench mark elevations are used.

The zero level for these gauge measurements referenced to local bench marks can be recovered from information in the Admiralty Datum Ledgers (Fig. 5.2 and see Appendix 5.1 for details) and from notes in the published Admiralty tide records. Hence, annual average MTL data from 1832 to 1838 referenced to local datums for these dockyard sites has now been recovered. Fig. 5.5 shows the Dockyard locations. Fig. 5.11 shows the simultaneous monthly MSL values for the four Dockyards.

5.3.2. Admiralty short term "campaign" surveys

The Hydrographic Office Archives in Taunton contain hand-written ledgers of Tidal Levels and Datums recorded during short term hydrographic surveys for the Admiralty Charts which were carried out to best survey practice guidelines (Admiralty, 1862; Hydrographer of the Navy, 1969). A typical example from the Tides Ledger (Fig. 5.3) shows Admiralty parameters for Padstow, Cornwall.



Padstow. Chart datum is 26·50 ft. below the top of the quay, or 11·16 ft. below Ordnance datum, or 29·06 ft. below an Ordnance B.M cut on corner of a house on the Quay, Padstow.

Tide levels, from observations 1834 & 35, adjusted to above datum.

M.H.W.S. 21·66 ft. M.L.W.S. 1·18 ft.

M.H.W.N. 17·42 · M.L.W.N. 4·66 ·

M.T.L. 11·18 ft.

H.W.F.&C. 5 H. 13 M. L.W.F.&C.

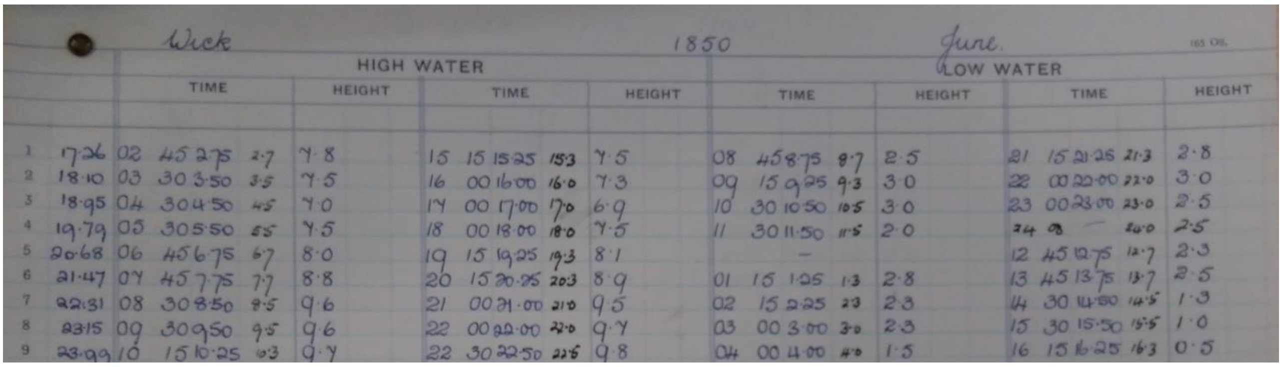
H.W.Q 4 31 L.W.Q

Figure 5.3: Example of entry in the UKHO Tidal Ledger, here showing summary of tidal information for Padstow. The MTL values were derived from observations of high and low waters recorded during Admiralty Survey campaigns, and were linked to OS bench marks. The information was often printed on local Admiralty Charts

It gives datum levels to a local bench mark, and states this is 11.16 feet below Ordnance Datum. The summarised calculations are based on observations from 1834 and 1835. The MTL is recorded as 11.18 feet referenced to the Chart Datum in 1834-5. Spring and Neap

High and Low Water levels are additionally calculated and tabulated. So are the High Water Full and Change times of High Tide after lunar transit, that is at times of Full and New Moon. H.W.Q. is the time delay after transit for Lunar Quadrature. These traditional terms are now seldom used. There is no information in this entry of the times of year the measurements are made so a correction for seasonal variations cannot be made. Many entries do have this seasonal information, and can be adjusted.

In total, the Tidal ledger has 168 entries for individual ports plus six in Ireland and two in the Channel Islands, as shown in Fig. 5.5. The observation periods are at least a single lunation (around 15 days) but in some cases extend to several years. The observation dates range from the 1830s to the late 20th Century as the chart datums were intermittently revised. Several other ports are up previously-navigable rivers; these include many ports which cannot be used here because values or datums were derived by comparison with water level observations at the coastal sites. A full list is given in Table S5.2 which shows how these ports are now numbered in the annually produced Admiralty Tide Tables (ATT). The order is as in the ATT listings, following the convention of anticlockwise numbering around Britain from the Scilly Isles in the southwest. We use this convention in this paper. Several of the ports in supplementary Table S5.2 have declined in importance and are no longer listed in the annual ATT publications. In a small number of cases copies of the tabulated daily records of HW and LW which relate to the summaries in the ledger have been stored in the PSMSL archives (e.g. daily HW and LW data from Wick recorded in April, May and June 1850), Fig. 5.4.



Wick 1850 June. 165 OS.

		HIGH WATER				LOW WATER			
		TIME	HEIGHT	TIME	HEIGHT	TIME	HEIGHT	TIME	HEIGHT
1	17.26	02 45 2.75 2.7	7.8	15 15 15.25 15.3	7.5	08 45 8.75 8.7	2.5	21 15 21.25 21.3	2.8
2	18.10	03 30 3.50 3.5	7.5	16 00 16.00 16.0	7.3	09 15 9.25 9.3	3.0	22 00 22.00 22.0	3.0
3	18.95	04 30 4.50 4.5	7.0	17 00 17.00 17.0	6.9	10 30 10.50 10.5	3.0	23 00 23.00 23.0	2.5
4	19.79	05 30 5.50 5.5	7.5	18 00 18.00 18.0	7.5	11 30 11.50 11.5	2.0	24 00 — 24.0	2.5
5	20.68	06 45 6.75 6.7	8.0	19 15 19.25 19.3	8.1	—		12 45 12.75 12.7	2.3
6	21.47	07 45 7.75 7.7	8.8	20 15 20.25 20.3	8.9	01 15 1.25 1.3	2.8	13 45 13.75 13.7	2.5
7	22.31	08 30 8.50 8.5	9.6	21 00 21.00 21.0	9.5	02 15 2.25 2.3	2.3	14 30 14.50 14.5	1.3
8	23.15	09 30 9.50 9.5	9.6	22 00 22.00 22.0	9.7	03 00 3.00 3.0	2.3	15 30 15.50 15.5	1.0
9	23.99	10 15 10.25 10.3	9.7	22 30 22.50 22.5	9.8	04 00 4.00 4.0	1.5	16 15 16.25 16.3	0.5

Figure 5.4: example of tabulated record of twice daily HW and LW for Wick for June 1850, transcribed from the same original data as used to compute the summary MTL in the Tidal Ledger

The International Hydrographic Bureau (IHB), through the mid-twentieth century, issued a series of loose-leaf sheets of tidal analyses including MTL or MSL information, worldwide. These values were supplied by each National Hydrographic Authority, in the case of Great Britain this was the Hydrographic Office. Almost all the UKHO Tidal Ledger information also appeared in the IHB series; we have scrutinised all these sheets and found additional ports and information which is not in the Ledger. Some of the large-scale Admiralty Charts and the annual ATT also contain summaries and updates of tidal survey information or metadata not found in the Ledgers. Data from these various Admiralty sources are cross checked and included in our analysis. High resolution scanned images of Admiralty Charts for the coast of Scotland are freely available from: https://maps.nls.uk/coasts/admiralty_charts_list.html and help give additional information for the Northwest coast, which is otherwise sparsely represented in Fig. 5.5.

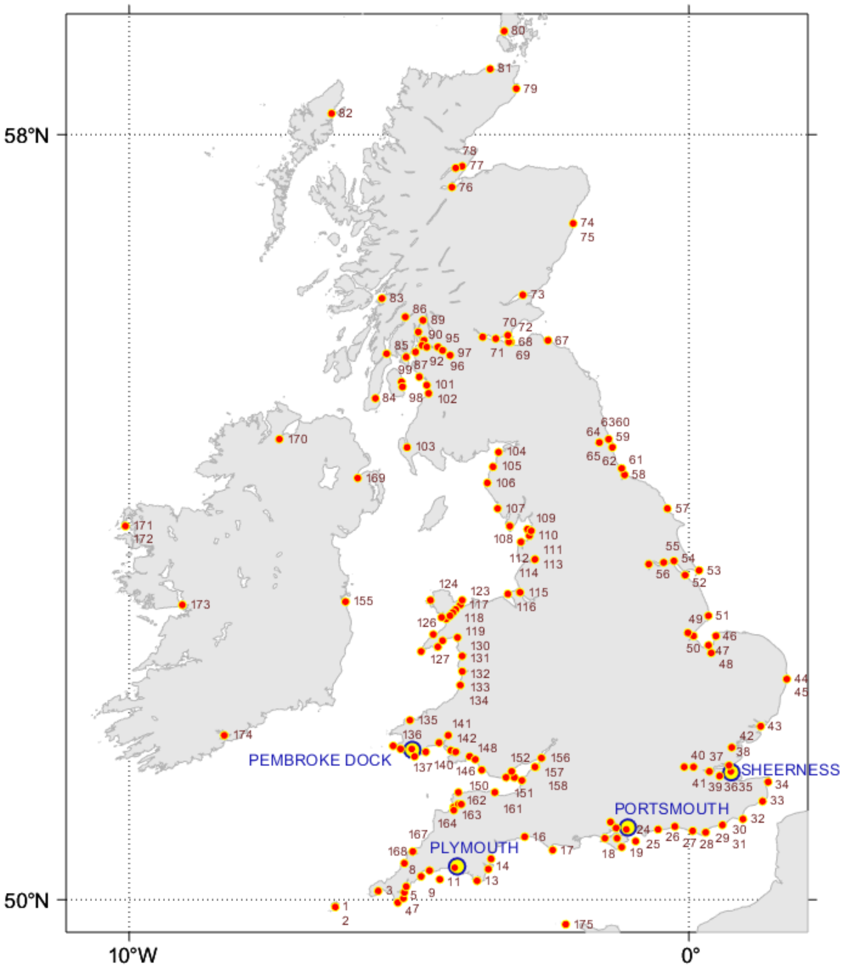


Figure 5.5: location of the four Admiralty Dockyards which have tide gauge records from the 1830s (blue open circles), and the sites of the harbours covered by the Admiralty Tidal

Ledger where additional early tidal measurements are available (numbers refer to sites listed in Table S5.4).

5.3.3. Ordnance Survey, First Geodetic Levelling (FGL).

As part of the early 19th Century triangulation of the UK by the OS, a few MSL observations were taken in 1838 in Northern Scotland (Clarke and James 1858, pg. 552). Only one of these (Rispond) can be securely connected to later OS bench marks. From 1840 to 1860, the OS carried out the First Geodetic Levelling of England, Wales and Scotland (FGL). Levels were referred to a nominal value of MSL at Liverpool (Ordnance Datum Liverpool, ODL), which was estimated from measurements made over a few weeks in 1844 (Thomson et al. 1879, Jolly and Wolff 1922). Towards the conclusion of the FGL, sea level measurements from 32 coastal stations in England and Wales, and 18 stations in Scotland were connected to local bench marks which were referenced to ODL. (Table S5.1, Fig. 5.6 and James, 1861a, 1861b). Most of these measurements were recorded by the OS over typically two weeks (average 15.8 days, approximating a semi-lunation at each site), using complete daytime tidal cycles (except for Sundays), observed at 10 minute intervals. HW and LW times and heights were also recorded to within five minutes and in most cases, to a twentieth of a foot (around 15 mm). Ordnance Survey (1861a) also includes some data from additional sites, most importantly the means of the Admiralty 1835-38 data (see above). Crucially, in all cases the tide gauge zero was levelled to nearby bench marks to high precision.

This 1859 OS data was first analysed in detail from a 21st Century perspective by Woodworth (2018), who shows that these measurements are a valuable addition to the 19th Century sea level data base. We incorporate this 1859 OS data systematically into our analyses, including many of the adjustments applied by Woodworth. Woodworth uses the averages of the 10-minute daylight readings, considering missing night-time data and any additional observations beyond the start and end HW and LW turning points, which might otherwise bias the mean values. In one or two cases, notably at North Shields, the OS sea level measurements are given as an average over a complete year.

A summary of similar OS tidal measurements made in 1896 was published in 1899 (Anon. 1899), and a table giving MSL values to ODL and ODN and brief details are given in Jolly and Wolff (1922). We also include this data, however, as in Woodworth (2018), we were also unable to locate any documents giving the exact dates of the observations, and therefore we cannot adjust these 1896 observations for seasonal or meteorological variations. This leads to larger uncertainties being associated with these values. Fig. 5.6 shows the 1859 OS measurement sites as well as PSMSL sites with more than 40 years of data.

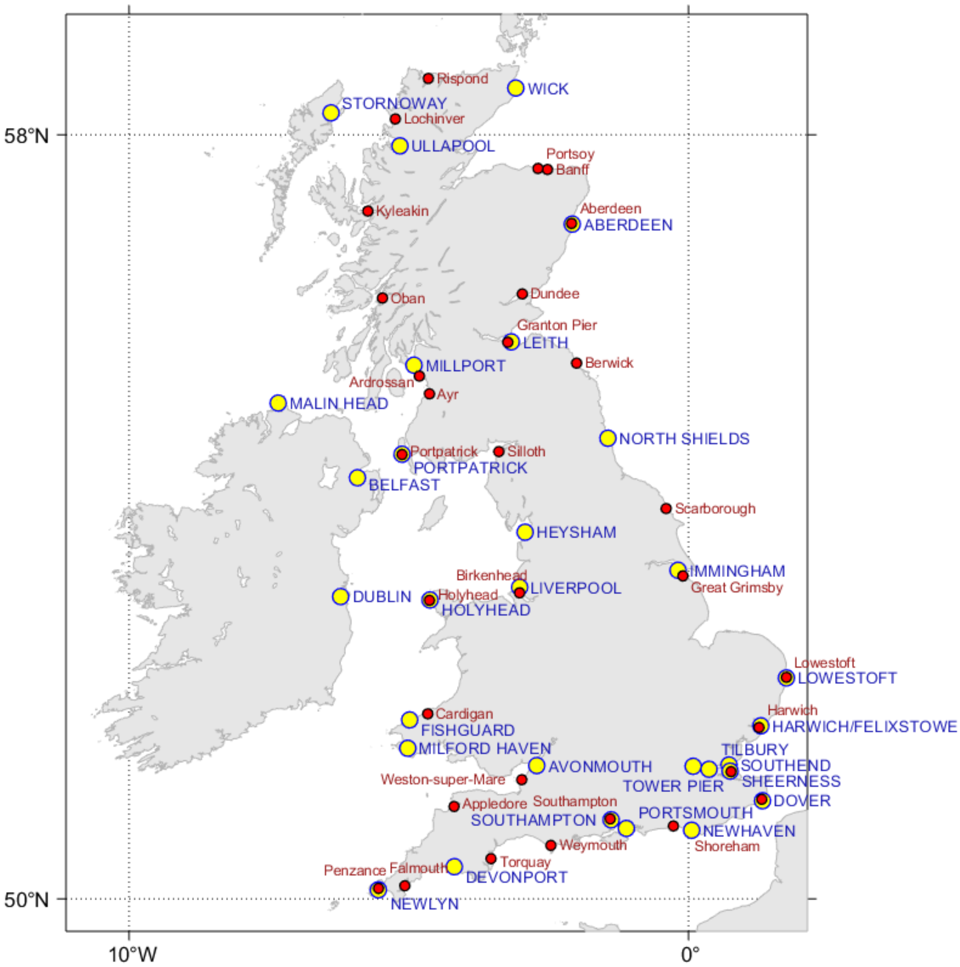


Figure 5.6: Blue circles with yellow fill, sites from PSMSL and metric extended reduced dataset with more than 40 years of recent data, and red: sites where sea level measurements were made for the FGL, 1840 to 1860.

The Ordnance Survey also carried out local sea level referenced surveys on island sites such as the Scilly and Channel islands, the Isle of Man (Neely 1930), Orkney and Shetland Islands. For these sites a MTL datum was usually established at an early date referenced to a local benchmark. In many cases this local Ordnance Datum has remained in use.

5.3.4. Continuous observations not in the PSMSL.

Initial scientific analyses of tides were based on long series of manual observations from docks such as London and Liverpool (Lubbock 1830, 1835, 1836, Whewell 1836a), but as these were often limited to HW observations only they are of limited use for MSL analysis. The installation of self-registering tide gauges was encouraged through the British Association for the Advancement of Science, and its sub-committees (Reidy 2009 gives a detailed summary). These provided continuous traces of the tidal variations, which were otherwise laborious to observe and record by hand even over a single tidal cycle. As well as the dockyard gauges, as early as 1833 a Mr Shirreff installed a self-registering gauge at Bristol after the pattern of Palmer and the records were published (Anon 1836b), but without a precise datum (the bed of the river was referenced). This gauge was replaced by a much improved one designed by Bunt in 1837 (Whewell 1838b, Bunt 1867). The data from Bristol is not used here as the site is too far upriver, but by the 1840s, the ports of Harwich, Dover and Ramsgate also had automatic gauges installed. Scientists were able to obtain and analyse these records which extended over much longer periods than previously and publish their results.

Data from such results that we have digitised and been able to connect to ODN include 19th Century data from Hilbre Island and Ramsgate (Thomson et al. 1873), Hartlepool and the Humber (Oldham et al. 1863, 1865), Dover (Baird and Darwin 1885, Darwin 1888, Roberts 1913), London (Redman 1877a, 1877b, 1883, Shankland 1932), Liverpool (Webster 1848, Bevis 1851, Lord 1855, Henderson 1857, Parks 1857, Schoolbred 1876a, 1876b, 1878, 1906), Dundee (Cunningham 1895), Hull, Grimsby (Shelford 1869), the Avon, (Mackenzie 1879), Clyde and Severn (Gibson et al. 1938).

We also include additional segments of continuous data from the BODC and from other recently published research (Spencer et al. 1988; Haigh et al. 2009; Edmeades 2015). The data from Spencer et al. is available at https://www.psmsl.org/data/longrecords/ancill_rep.htm

We also include data from recently installed harbour gauges at Shoreham, Scarborough, Whitby, Blyth, Buckie, Inverness, Cromarty, Oban and Stranraer, (data from other sites is available, but only these gauges appear to record over the complete tidal range) and we have applied similar quality control to this high frequency data and calculated monthly mean and annual MSL (as well as HW, LW and MTL) values. The raw data can be found at https://www2.sepa.org.uk/waterlevels/ and https://riverlevels.uk/

5.3.5. Campaign Survey data

Other shorter series of observations were also the subject of published scientific analysis. A series of high frequency observations from Southampton and Ipswich were instigated and analysed by Airy (1843). Whewell recorded Bunt's levelling work between Axmouth and Portishead (Whewell 1838a), from which we were able to recover MTL for Axmouth and Portishead for short periods of 1837 and 1838 and Wick Rocks in 1838. Additional data can be recovered from historical civil engineering records. In 1813 daily high and low waters were manually recorded between 27th March and 3rd August 1813 at various points on the River Tyne (by Francis Giles under direction of John Rennie). A portion of this data (22nd April to 11th June 1813) was published (Brooks 1867) and has been digitised for North Shields for this paper. Importantly, the bench mark cut into the stonework of the North Shields New Low Lighthouse in 1813 as part of this survey has been used as a vertical reference point ever since. This is possibly the earliest UK data available where both daily Low Waters and High Waters are recorded where the original bench mark still exists and was in recent use. Historical summaries of other very early (pre 1820) MTL are available for Liverpool, Sunderland, and Portpatrick. Wherever the data span covers two weeks or more and a recovered tide measurement datum can be referenced to ODL or ODN, this data is included in the analysis (e.g. Wallis 1899, Shankland 1926). Some early high frequency manually observed MSL (often over separate spring and neap tidal cycles) has also been published (Beardmore 1852). Though too short to be included in this analysis, they can still provide useful datum and quality control information, particularly for any overlapping longer MTL series. Other continuous records are alluded to in some analyses, but either no data is provided or only short extracts are published (Robertson 1869 (Leith), Bowden 1956, (Shoreham 1953), Cartwright and Crease 1963 (Ramsgate 1957 and 1958)).

For background information, Ireland was surveyed through the 1830s. Linked to this, the Ordnance Survey of Ireland measured sea levels at 22 sites in the summer of 1842, over two months, to fixed bench marks as part of their Irish mapping and levelling campaign (Airy 1845a). Data from three sites, Courtown, Castletownsend and Ballycastle, have been compared with recent measurements (Pugh, 1982). Measurements in Ireland to fixed bench marks were continued in 1850 and 1851, by the Royal Irish Academy (Haughton, 1854, 1865). Irish data are not included in our analysis. An integrated analysis of Irish sea levels is now available in pre-print (Pugh et al. 2021, in review) to which this author contributed.

5.4. Data adjustments and corrections

Table S5.3 in the supplementary material summarises the various factors to be considered.

Throughout, the term "adjustments" is used to describe processes where we attempt to reduce variability (formally statistical variance, though we often use standard deviations as a measure) in the observed sea level caused by factors like local meteorology. This is distinct from "corrections" where we attempt to remove external sources of error in the sea level records, such as incorrectly set TGZ. Comparing older sea level measurements with recent PSMSL values requires an understanding of how the instrumentation and analysis methods as well as the reference datums and local site environment have changed. The early data are almost always MTL in feet, and to ODL. These must be converted to metric units (we use mm), to MSL, and referenced to the same revision of ODN as used in the most recent tide gauge levelling. Many older measurements are for short periods, much less than a year, and an adjustment for the average seasonal variation is necessary, which is derived from a long series of quality controlled monthly MSL data from a suitable nearby site.

Major dredging campaigns, sand bar removal and pier construction from the mid-19th Century onwards have also affected tidal regimes upstream of the river mouths of several ports, so data from sites some distance from the open sea require careful assessment (Familkhalili and Talke 2016; Talke and Jay, 2020, Talke et al. 2021). In making these adjustments, it is important also to quantify the confidence with which each adjustment can be made.

When comparing the data from all sites (section 5.4.7), we make use of the understanding that corrections for datum errors are site specific and not correlated, adjustments for GIA and meteorological components are highly correlated locally, but can vary substantially around the country, whilst components due to more distant ocean variability are expected to be more consistent from site to site.

5.4.1. MTL to MSL.

MTL, the average of High and Low Water heights over some defined period, is easily computed and so was generally favoured in the 19C and later. However, MTL is not the true MSL, obtained by averaging regularly sampled (typically hourly) levels over a period, and the difference can be as much as several centimetres. For a fuller discussion see Pugh and Woodworth (2014), Appendix C, and Woodworth, (2016). An approximate correction (in a predominantly semidiurnal tidal regime such as around most of the UK coast) can be calculated based on the amplitude of the M_4 constituent and its phase relative to that of M_2.

For many sites modern high frequency measurements (sampled every 10 or 15 minutes) over a number of years are available, allowing MTL and MSL to be derived directly from the data. The difference (including any nodal corrections (Woodworth 2012), see below) is systematic and can be assumed to hold for older data assuming the tidal regime has not changed. This observation based method is used where possible. For sites where high resolution data is not available, an estimate of MTL-MSL can also be found by directly synthesising a period such as a year of High and Low Water levels for a port from known tidal constituents, relative to a zero MSL. MTL-MSL is then the difference of the means from zero. This approach has been used here for some sites with predictions provided by Philip Woodworth, for the year 1989. Where the above methods are not possible, an estimate can be made using (MTL-MSL) values for the northwest European shelf plotted by Woodworth (2016). Some caution is required: as Woodworth (2016) shows, including a full set of higher harmonics such as M_8, can make a difference of a few tens of mm (21 mm for Liverpool), and these higher harmonics can be very locally generated. In many cases the exact location of the original measurements is not known, so uncertainty in this adjustment is increased. In addition, the assumption of an unchanged tidal regime may not hold (Mawdsley et al. 2015). Around the GB coastline, many harbour and river channels were altered by dredging campaigns in order to accommodate ever-larger vessels, again adding to uncertainties for sites some distance upriver. In column 7 of Table S5.4 the MTL adjustment values are given for many of the ports which are centres of clusters, a concept to be introduced in the next section. The average adjustment is -18 mm, with a mean absolute difference of 56 mm at individual sites. The adjustment is significant.

The 1859 adjustment (OS data, section 5.3.3) to be added to MTL ranges from -139 mm at Sheerness to 143 mm at Plymouth. However, it changes over a nodal 18.6 year tidal cycle. Fig. 5.1s in the supplementary material shows the changes based on annual predictions at Southend over the period 1829 to 1848. There is a 7.1% modulation, a range of 23 mm with the smallest difference, -138 mm in 1839, when the nodal factor is near a maximum, and the semidiurnal tidal range is least. The maximum difference, -162 mm is in 1829 and 1848. This is small compared with other uncertainties, so nodal adjustments are only made for Sheerness and Plymouth. The MTL to MSL adjustments (where used) are given in column 7 of Table S5.4 in the appendix.

5.4.2. Ordnance Datum Liverpool to Ordnance Datum Newlyn.

In order to reduce all MSL observations to a common datum, at least locally, we must account for any changes in datum over time. Very early 19th Century data was often referred to fixed local datum points such as a dock sill. Later in the 19th Century UK sea levels (and the older datums) started to be referred to ODL, which was transferred around the country during the First Geodetic Levelling (FGL), 1840 to 1860. Subsequent local relevelling meant that revisions were made to ODL bench mark elevations up to the 1900s (Burnett and Carmody 1960). A Second Geodetic Levelling (SGL) was undertaken by the OS between 1912 and 1921, with ODN heights ultimately expressed relative to MSL at Newlyn from 1st May 1915 to 30th April 1921 (Henrici 1920, Jolly and Wolff 1922; Close 1922a, 1922b, 1923). The SGL was not extended to southeast England until 1946-51, and not to Scotland until 1936-1952. A Third Geodetic Levelling (TGL) 1951-1959 was adjusted to closely fit the elevations of the SGL Fundamental bench marks located every 50 km or so (Kelsey 1972). Hence, differences between ODN levels from the SGL and the TGL are usually small. The modern PSMSL GB RLR sea level measurements are referenced to a set of nearby TG bench marks connected to this third version of ODN.

Here, wherever possible, we resolve the local OD elevation differences in different time periods using documented levelling connections between individual benchmarks, thus allowing connection of the older sea level measurements to the latest revision of ODN. This allows for any network datum elevation changes due to local revisions in ODL or ODN, and allows preferential selection of stable bench marks near the tide gauge site. This differs slightly from the method of Woodworth (2018), who used the 1 km gridded conversion values provided at the OS website:

https://www.ordnancesurvey.co.uk/gps/legacy-control-information/liverpool-to-newlyn. Individual bench mark information to ODN is tabulated by the OS in one-kilometer grid squares for all of Great Britain at: https://www.ordnancesurvey.co.uk/benchmarks. For each km square, this site gives details of bench marks: grid reference, mark type (e.g. cut mark, rivet, flush bracket) height in mm to ODN and previous datum revisions (sometimes including ODL), levelling order (First, Second or most commonly Third order of accuracy), year of leveling or verification, and the height of the mark above ground to ease relocation. Most bench marks on this list were last visited from 1950 to the early 1980s. The ODN-ODL differences vary systematically and locally across Great Britain (Fig. 5.7).

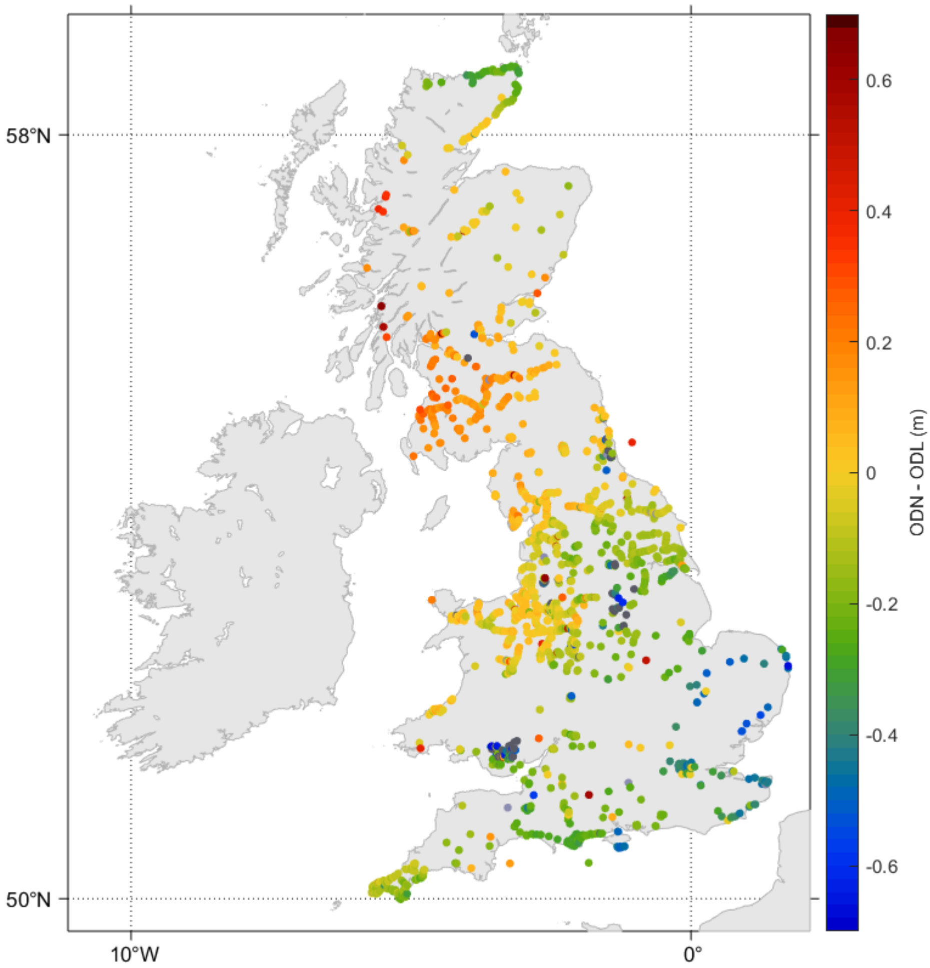


Figure 5.7: plot of ODN minus ODL elevation differences for all 3023 bench marks in the OS database which have both ODN and ODL values. This is broadly similar to Fig.2 in Woodworth 2018, see above.

The elevations of these and many other older bench marks not in this list were printed on large scale OS maps and town plans from the 19th and early 20th Centuries, from which we have extracted a significant amount of additional bench mark information. Elevations are usually given to a tenth of a foot but sometimes one-hundredth of a foot. These maps are freely available from the digitized collection of the National Library of Scotland at: https://maps.nls.uk/os/. Early OS maps as well as revised versions up to the late 20th Century (with elevations to the later revisions of ODN) are also available (for a monthly subscription fee) at: https://www.old-maps.co.uk.

In the UKHO tide or datum ledger a TGZ or ACD elevation is typically given in feet below one or more bench marks, as well as the bench mark elevations above ODL (or ODN). Even if the original bench mark no longer exists, a modern elevation to ODN can be estimated by comparing contemporaneous elevations of the original and nearby bench marks (taking care that such elevations are referred to the same ODL or ODN revision) provided some of these also have modern ODN elevations, or in turn can be connected to bench marks with modern elevation values. Confidence in these geodetic connections and adjustments can be increased by comparing many pairwise connections of bench marks with old and new elevation values.

Table S5.4 in the supplementary material shows the bench marks that had been levelled to both ODL and ODN for the four Admiralty Dockyard sites. Local inspection showed that several of these marks were extant and robust in 2016 and 2017, as indicated by an asterisk. The stability of the results is good, as indicated by the standard deviation of between 10 and 30 mm at all four sites. For Sheerness the bench mark at TQ 9169 7475 (in italics), where the difference is four standard deviations from the mean, is excluded as the mark has probably been displaced. Similarly, for Plymouth the bench mark at SX 3485 5469 across the River Tamar from the dockyard, was omitted.

Over one thousand bench marks with both ODL and ODN levelling were found at 90 coastal locations. At Pembroke Docks for example, 144 recorded elevation values were compared for 50 local bench marks (with 19 of these from the original 1841 and 1850 levelling). Conversely, only two usable bench marks were found for Kinlochbervie. Extensive port development, for example at Southampton, is a major limiting factor for long-term stable bench marks. The adjustment of ODL to ODN varied from subtracting 610 mm at Harwich, to adding 611 mm at Oban. A few rogue marks at other sites were excluded, and some local anomalies are discussed later, but overall the average standard deviation of the differences for groups of bench marks at a particular site was 21 mm. Adjustments to 20th C standards for our 19th C sites are included in column 8 of Table S5.4.

The small standard deviations at each site confirm the underlying assumption that despite large deviations at national scale (Penna et al. 2013), the general accuracy of the levelling locally (and to some extent regionally) is of order 20 mm.

A direct comparison of our ODL to ODN adjustments with those tabulated in one-kilometer squares by the OS is problematic, as at some sites ODL elevations were significantly revised (e.g. at Pembroke Dock the 1841 and 1850 bench mark elevations were revised by around 150 mm in the 1860s, and then revised back again in 1906). Unless bench mark elevations (or in rare cases OS map revisions) are stated in the Admiralty tidal or datum ledgers, this can be a potential source of uncertainty. In the few cases where information is lacking, we assume the latest map revision available at the time was used.

5.4.3. GIA adjustments

The RSL data is adjusted for the ongoing different post glacial rebound rates around the British Isles (Emery and Aubrey 1985; Peltier and Tushingham 1989; Rennie and Hansom 2011; Whitehouse 2018) using the Peltier ICE-6G_C (VM5a) GIA model data, which includes the effect on measured sea level via both VLM and gravitational effects. The GIA adjustments for each precise site location in mm/yr (column 19 of Table S5.4 in the appendix) are interpolated from the 0.2 degree gridded GIA model provided by Peltier, and are used to derive a vertical offset adjustment for each site for each year or time period. The intercept or zero offset time value is here defined as the OS levelling date of the local Fundamental Bench Marks (FBM) used in both the SGL and TGL campaigns (column 18 of Table S5.4), thus all MSL values are referenced to local ODN. To obtain the local Relative Sea Level Rise (RSLR) as it would appear without GIA, the GIA adjustment must be subtracted from the total SLR estimate for each cluster.

Other GIA models are available for the UK, as are CGPS (Continuous Global Positioning System) observation based estimates of recent vertical land motion for a limited number of locations. Those we looked at were similarly effective in reducing the scatter in the derived SLR trends, and we discuss this briefly in section 5.6.

5.4.4. Seasonal adjustments

Some of the campaign data observation periods were only a few months, or an average of two weeks for the OS 1859 data. In order to treat these shorter periods of data as representative annual averages, an adjustment for the average seasonal variation (Fig.5.8) is necessary, and the associated uncertainty will also be larger than for annual values. Using detrended monthly data from the nearest “core” PSMSL site defined in section 5.4.7 (with datum offsets adjusted) we estimate the annual and semi-annual sinusoidal components using linear regression to create an average seasonal curve which is then interpolated to daily resolution for each core site. We then take an average of this seasonal signal between the start and end dates of the MSL data, giving a seasonal offset adjustment from the annual mean. This is then subtracted from the mean MSL over the same period. These adjustments can be of the order of 100mm. The uncertainty for the seasonal adjustment is also derived (see section 5.4.6). Fig. 5.8 shows the similarity of the average seasonal monthly MSL variation around the GB coastline, but also shows how the amplitude of this component increases with latitude (Tsimplis and Woodworth 1994; Dangendorf et al. 2013) for the 36 TG locations defined as core sites in section 5.4.7. The seasonal adjustment is given in column 11 of Table S5.4 in the appendix.

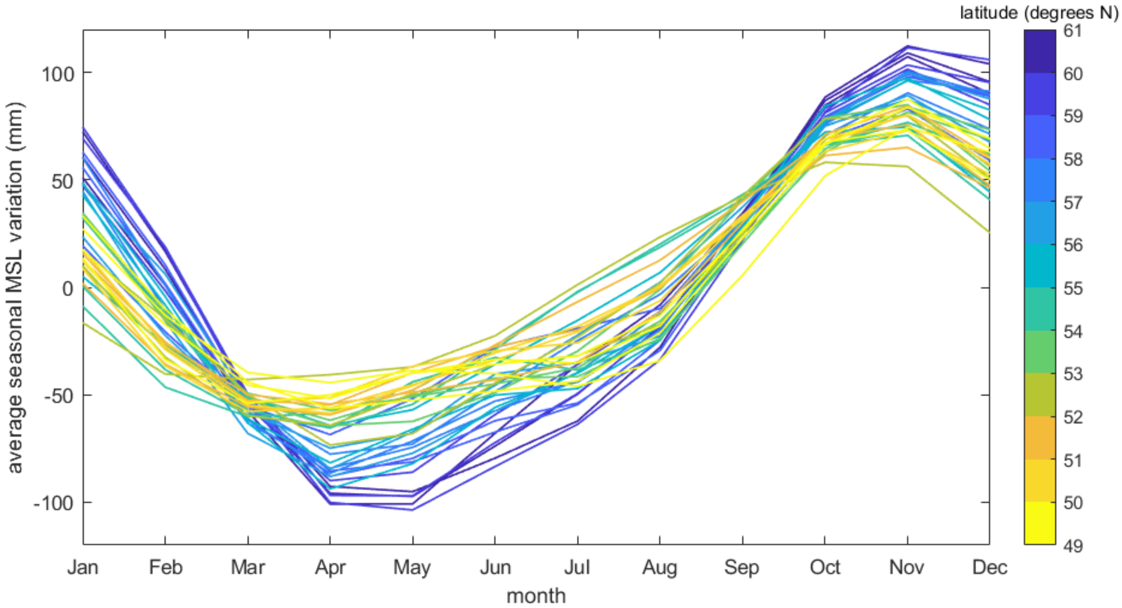


Figure 5.8: the average (over length of each record) seasonal variation in MSL for the 37 'core' PSMSL TG sites around the GB coastline, showing the phase relationship and progressive increase in amplitude from South to North.

5.4.5. Meteorological variability: extending and testing a barotropic model

Sea level variability due to local meteorological influence between Jan. 1958 and Dec. 2018 is estimated using a barotropic tide and surge model, CS3X, a variant of the UK's main operational tide-surge forecast model (see Hogarth et al. 2020 and references therein). Model outputs are available from the NOC (see overview on https://noc.ac.uk/files/documents/business/model-info-CS3X.pdf). Using a barotropic model has been found to be an effective way of removing sea level variability due to both local winds and atmospheric pressure (Piecuch et al. 2019), leaving a residual which is much more uniform round the UK and attributed to far-field influence (Hogarth et al. 2020).

No high resolution barotropic models currently extend back as far as the early 19th Century, so here we first create an extended sea level air pressure and geostrophic wind data set at each tide measurement site using interpolated 1 degree gridded observations from the recently released 20th Century Reanalysis version 3 (20CRv3) (Slivinski et al. 2019) which extends back to Jan. 1836, combined with interpolated 5 degree gridded data from a reanalysis of historic European air pressure data sets (Luterbacher et al. 2002) prior to 1836. Discontinuities are minimised by using linear regression to develop coefficients to adjust the monthly Luterbacher et al. pressure data for mean level and variability at each site taking advantage of the large temporal overlap with 20CRv3 data. Similarly we extended the geostrophic wind components prior to 1836 using computed pressure difference values from grid points North and South as well as East and West of the site location from the Luterbacher et al. data. The new time series at each site are then checked both visually and by comparing with other reanalysis products, including HADSLP2 (Allan and Ansell 2006), noting that a previous version of 20CR, (version 2c) has documented anomalies which lead to poor estimates of global MSLP over the ocean in the mid 19th Century, which can lead to time specific anomalies in Inverse Barometer (IB) adjustment values. These anomalies are not visible in 20CRv3 (or HADSLP2).

Next, the simulated monthly sea level from a version of the CS3X tide and surge model covering Jan. 1958 to Dec. 2018 at each site is linearly regressed using the extended air pressure and wind dataset (with pressure and wind as predictors), to give us a statistical barotropic model covering the period 1813 to 2018. The seasonal cycle is removed from both the barotropic model and the meteorological data to avoid double counting any seasonal variation. We then test this model with deseasonalised tide gauge data, and we demonstrate reduced variability in long MSL records (e.g. Aberdeen). Regression using a tide and surge model rather than the MSL observations ensures that only the locally driven component of variability is being simulated, allowing separation of this from other components present in the MSL record.

For short periods of MSL data (less than 1 month) we use daily meteorological data from 20CRv3 after 1836, or for data prior to 1836, interpolate the adjusted Luterbacher et al. (2002) SLP and geostrophic winds as for the seasonal adjustments above. We check that the differences between mean daily data and interpolated monthly data are low after 1836, and assume this holds before 1836 where we have not yet obtained data at daily resolution. These adjustments are given in the 12th column in Table S5.4 in the appendix.

5.4.6. Uncertainties.

For interpreting the 19th Century values we need an appreciation of the uncertainty in the various adjustments. Table S5.3 also identifies the sources of uncertainty in each adjustment. Later we will fit weighted trend lines, where the weights are based on these uncertainties. The SLR trends at each site are adjusted with an estimate of GIA, which also has a significant uncertainty, briefly explored in section 5.6.

For MTL to MSL the uncertainty where predictions are possible is 20 mm, but an unquantifiable uncertainty comes from local shallow water variations in tidal ranges. The 20 mm estimate is thus optimistic. Also, the MSL may increase locally up estuaries and in rivers. In some cases, local distortions will cause outliers which can be identified from the plots. This remains one of the biggest local unadjustable uncertainties.

The uncertainties in the ODL to ODN adjustment are based on the standard deviation within the ODN-ODL differences for individual bench marks at each location. These have an average of 15 mm standard deviation. Outliers exist: the differences for Sunderland and River Tees Entrance show a standard deviation of over 100 mm, possibly attributable to local subsidence.

Within a cluster (see below) transfer of levels from other sites to the core location will introduce uncertainties in the levelling. Although impossible to be sure of the relative components, these transfers were a mix of secondary and tertiary levelling. Harley (1975) gives a confidence limit of:

$$N \sqrt{separation\ in\ km}$$

in mm, where N is 2, 5 and 12.5 for OS Primary, Secondary and Tertiary levelling respectively. We use a pessimistic value of 8.5, which is the mean of Secondary and Tertiary levelling. For example, a 15 km levelling (the average distance between sites) will have a standard error (SE) of 32.9 mm. The greatest distance between sites in a cluster is around 136 km, giving a worst case levelling uncertainty of order 100mm. Some of the sparsely spread sites are in Scotland where there may be additional error sources due to levelling over dynamic terrain. For Primary Levelling a 1000 km line would have 66 mm confidence limits, whereas we see in Fig. 5.7 the differences on a National mapping are both systematic and an order of magnitude greater than this (Edge 1959). Also there are unexplained jumps across the Wash, and the Severn Estuary.

For the seasonal adjustments, the variability in storm-prone Winter months is expected to be significantly higher than for Summer months. This can be confirmed by calculating the standard deviation of differences from the mean for each month over many years.

Because many periods in the data set do not extend for a full year (some are as short as two weeks), a related important question is how these standard deviations increase as the length of the data observations is reduced to less than 12 months. The uncertainty as a function of time of year and the length of observation can be represented as a point on a continuous surface, as in Fig. 5.9. This shows, for Newlyn, the variation in standard deviation (including that due to barotropic variability, i.e. before adjustment) both seasonally and for data spans of one to twelve months of de-trended monthly MSL data. Clearly, a short period of data recorded in the summer months is likely to be more reliable than over the same period in the winter.

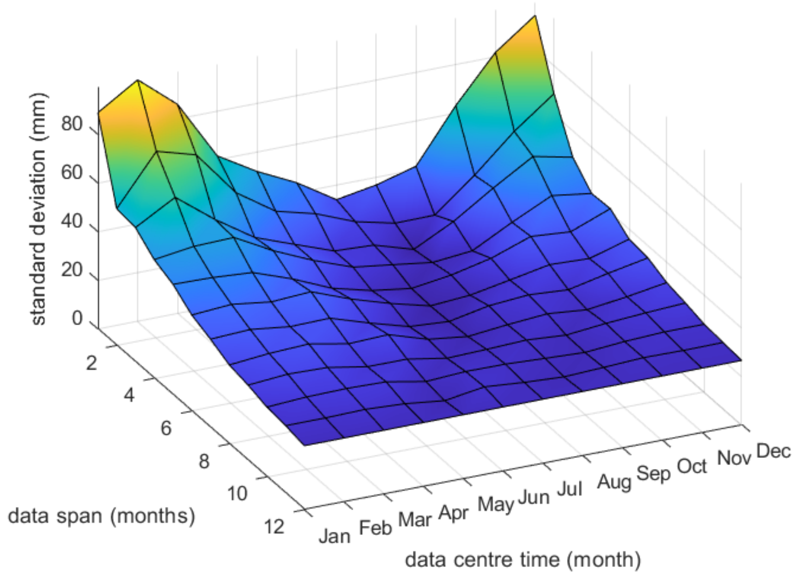


Figure 5.9: plot of estimated seasonal uncertainty for Newlyn showing variation with time of year and period of observations. Similar grids are generated for each core PSMSL site.

We generate a matrix of repeated uncertainty values covering three years (not shown in Fig. 5.8) to simplify the estimation of adjustment values for dates overlapping year end.

The combined uncertainty for each site, given in column 23 of Table S5.4, is estimated as the individual uncertainties added in quadrature.

5.4.7. Partitioning the coastline into regional clusters.

Table S5.4 in the appendix summarises the useable data sources, adjustments and uncertainties. The Ordnance Datums represent a nominally level surface, as determined by large scale levelling exercises. However, levelling errors at the several decimetre level over a national scale (Penna et al. 2013) are too large to allow direct comparison of widely spaced tide gauges. To overcome this in a systematic way we divide, somewhat subjectively, the coastal areas around Great Britain into local clusters, based on regional and expected hydrodynamic proximity. For example, Milford Haven is expected to have different characteristics than the nearby Cardigan Bay region, centred on Fishguard. Some of the clusters may contain more than one PSMSL site with recent data, in this case, for each cluster, the PSMSL site with the maximum number of valid years of recent data, levelled to modern revision of ODN, is chosen as the core site. These clusters are shown colour coded in Fig. 5.10. Within each local cluster it is assumed that:

- OS levelling (ODL and ODN) is accurate, within computed standard errors (see above)
- The mean dynamic sea level is horizontal
- Generally, unless we have information to the contrary, the average MTL-MSL value is constant

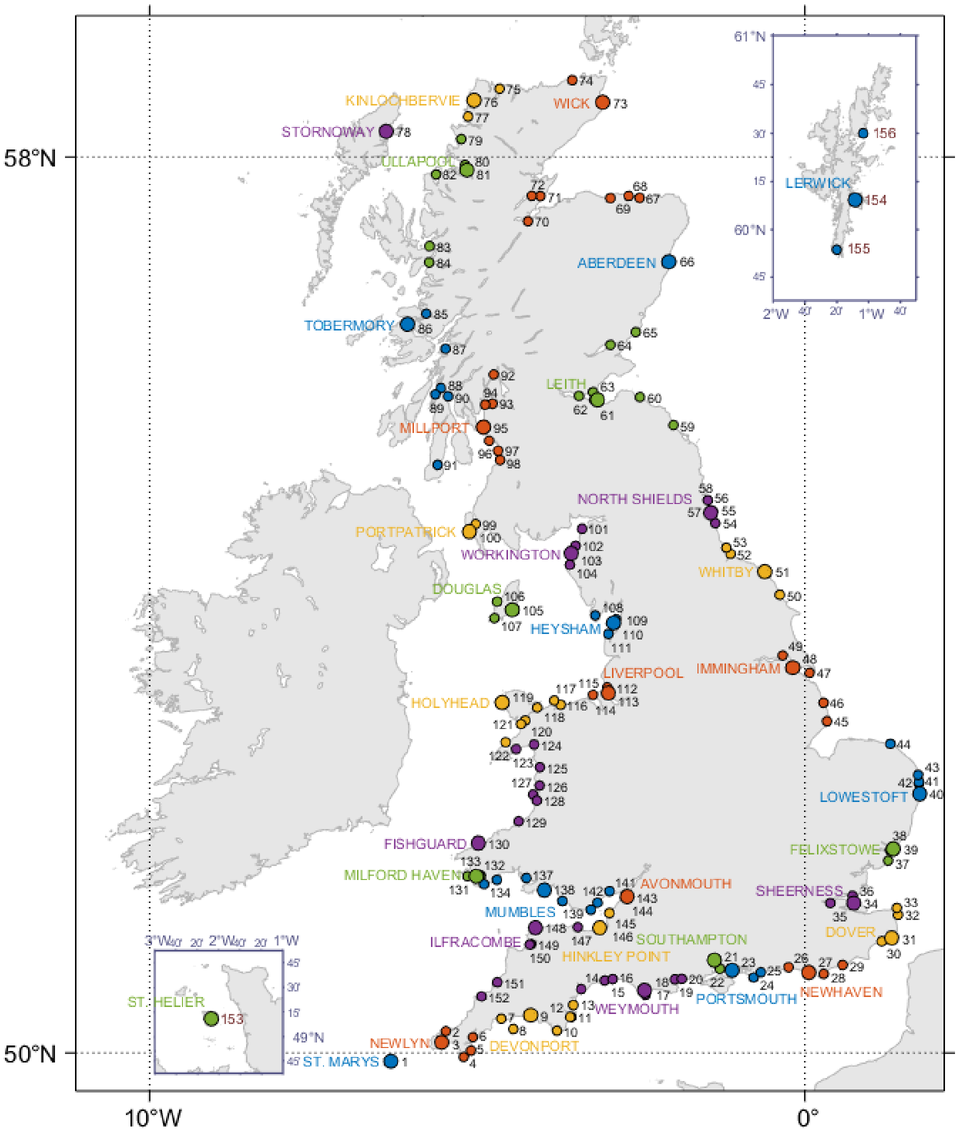


Figure 5.10: All sites where data is available, colour coded differently to identify each local cluster. The core PSMSL site for each cluster is shown as a larger marker and is named. In a small number of cases where sea level dynamics (or possibly unaccounted levelling or datum errors) introduce clear sea level offsets (relative to ODN) in geographically close stations, these are treated as separate clusters (e.g. Avonmouth and Southampton).

5.5. Results

It is now possible to look at trends separately in the 36 individual clusters, and assess the value of adding the older data to the PSMSL holdings. Plots for all clusters are available in the online supplementary material. Table S5.4 shows the year and length of data from each source in columns 1 and 2. In section 5.2.1 we noted that only a handful of the existing PSMSL series contain data from the 19th Century. Three RLR sites have data from prior to 1895, two prior to 1862, and only one has data (Sheerness, 15 station-years) prior to 1858. By utilising the new data sources, almost all 36 clusters now have spans exceeding a century, whilst an extra 1635 station-months or 136.25 equivalent station-year datapoints are added prior to 1900; 833 station-months or 68.7 station-years of these are prior to 1858. These include the important addition of sections of monthly MTL data from the 1830s to the existing series for the four Naval Dockyards: Sheerness, Portsmouth, Plymouth and Pembroke Dock (Fig. 5.11).

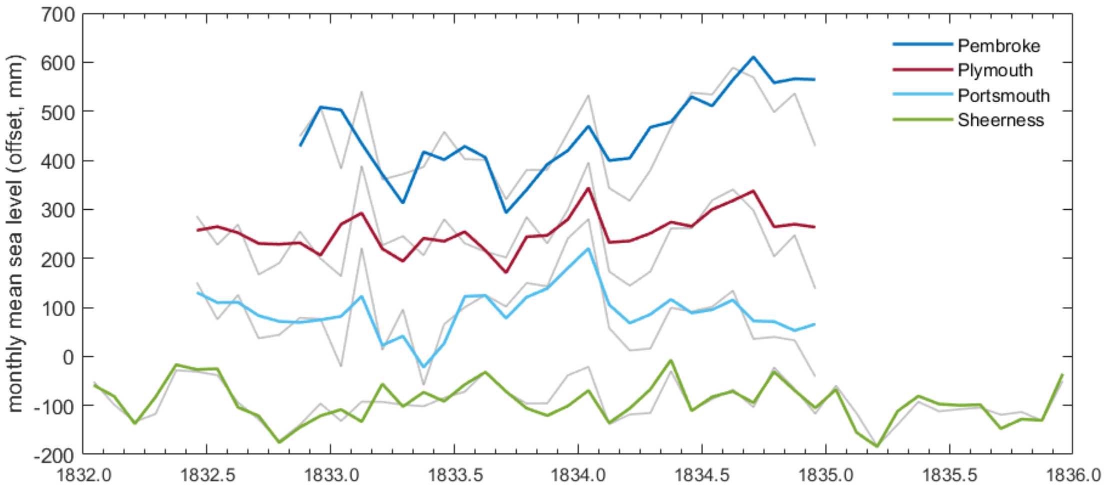


Figure 5.11: Estimated monthly MSL at the four Naval Dockyards, the background grey traces are unadjusted for meteorological effects, the coloured bold lines are adjusted. Series are offset to aid visualisation.

We will now briefly review the data from these four locations as examples. Each cluster has a letter assigned to it which is listed in the first column of Table S5.4 in the appendix. For all four Dockyard sites the 1830s datum information from the Admiralty Datum Ledgers and original documentation was vital. Each plot also has the adjusted and extended monthly MSL for Sheerness plotted in light blue to give a visual reference and indication of the variability we might expect in a typical record at monthly resolution, as well as of the relative differences (offset) between local ODN and local MSL. This helps comparison between the different cluster time series.

5.5.1. Sheerness, cluster I.

Fig. 5.12 shows the plot of MSL data from Sheerness. Existing observations (PSMSL) at the core station (Sheerness) and two other local PSMSL sites (Southend, 10 km across the Thames Estuary and Tilbury, around 33km upriver) are shown as smaller open circles. Open diamonds show OS sites from 1859 or 1896. The larger open circles are new data from all sources. All sites are colour coded for location. The grey uncertainty bars for the new data are combined uncertainties from levelling, meteorological, seasonal and MTL to MSL adjustments.

For Sheerness, the PSMSL already holds some data from the 1830s, as MSL referred to ODN. We recomputed the MTL for 1832 to 1843 from our digitised values, and also checked against the OS (1861) averaged values for 1835 to 1838. The OS 1859 value is aligned with the other points, within the uncertainty levels. The Southend values also agree within the uncertainty limits. Tilbury and Gravesend (across the river) are far enough upriver to suffer potential increased mean water levels due to the slope of the river. We can observe that a) we would need to subtract a centimetric scale offset from the Tilbury MSL data to minimise the mean difference from the Sheerness data, and b) an identical offset subtracted from the Gravesend 1840s data would result in a similar reduced difference. We will return to this concept in section 5.5.7. Other nearby tidal observation sites are given in the Tidal Ledger, but are not used: Osea Island is not connected to Ordnance Datum, though local bench marks are defined in the Ledger; Chatham levels in the Ledger are computed by comparison with Sheerness so are not independent. Finally, levels further up the River Thames at Woolwich and London Bridge are excluded because of probable freshwater flow effects (although annual variations are highly correlated). Note that for Sheerness the (MTL-MSL) adjustments took account of nodal variations.

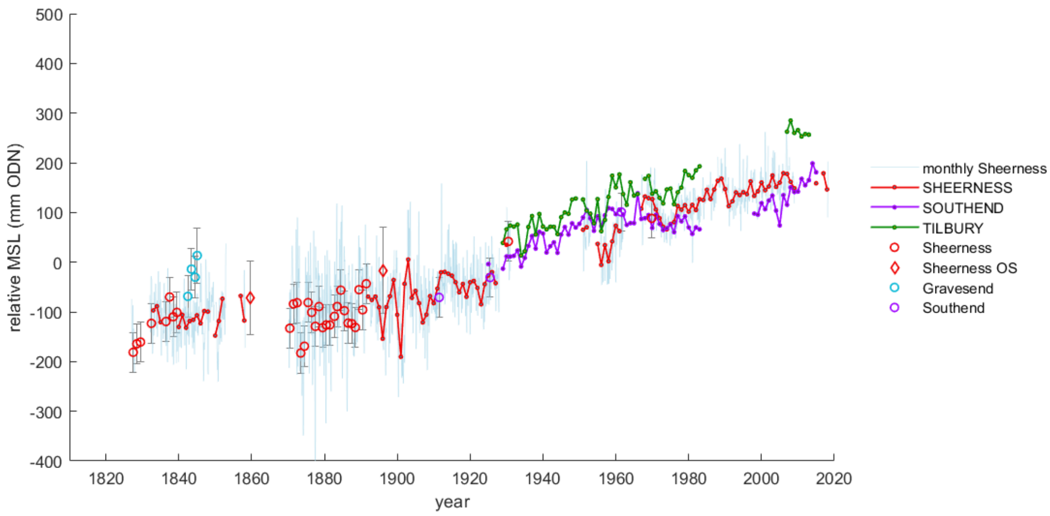


Figure 5.12: plot of data from Sheerness and Southend, resolved into annual MSL values, overlaid on fully adjusted monthly values (light blue) for Sheerness. The filled points (connected by lines if an adjacent value exists) represent existing annual MER (extended and adjusted PSMSL) MSL data. All new data values are represented as larger open circles

(or open diamonds for the OS observations) and have total uncertainty estimates shown as grey bars.

5.5.2. Portsmouth, cluster F.

Fig. 5.13 is the MSL plot for the cluster around the core site of Portsmouth. The cluster region extends from Portsmouth to Bognor Regis. Values from the offshore Nab Tower were excluded, as there appear to be (typical) levelling issues across bodies of water. Southampton Water, Southampton and Calshot, are grouped elsewhere in the Ledger. The apparent elevation offset difference between Portsmouth and Southampton PSMSL ODN referenced water levels may be due to hydrodynamic factors, or local levelling, or both, but is large enough to justify treating them as separate clusters, a point we will return to later. For Portsmouth, the PSMSL hold monthly RLR MSL from 1961 to 2018, and a year of Metric monthly data from 1930. We resolved the datum offset for the 1930 Metric data, added a small number of additional recorded points from Portsmouth and nearby sites, as well as the important 1830s adjusted MTL Dockyard values.

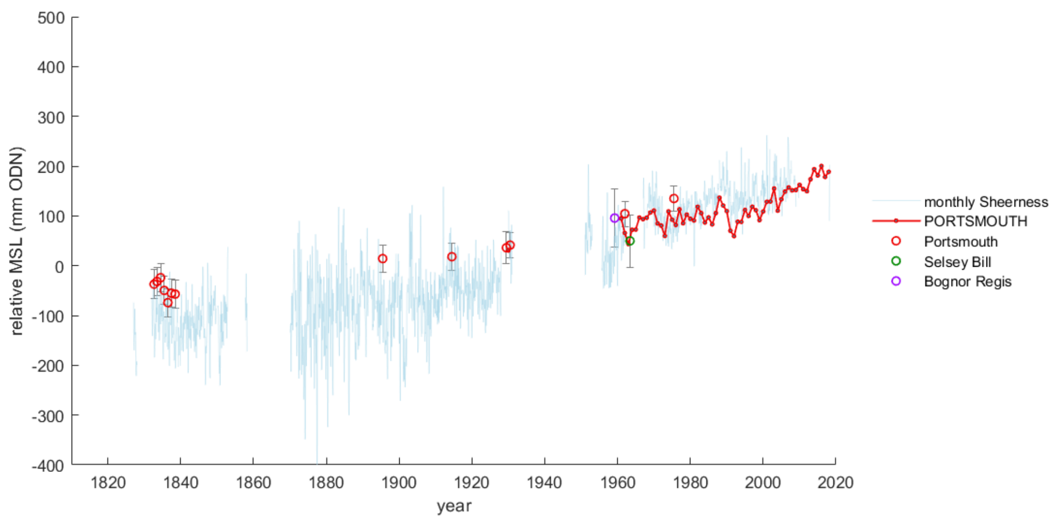


Figure 5.13: Plot of Portsmouth data cluster, overlaid on the monthly Sheerness data to help comparisons between cluster time series.

5.5.3. Plymouth, cluster C.

Fig. 5.14 shows the Plymouth cluster and trends. As some of the cluster sites are up creeks we might expect some hydrodynamically elevated values. Without local modern data it is also difficult to estimate MTL to MSL conversion factors. For Devonport, the PSMSL hold monthly MSL from 1961 to 2018. We assume this to be more comparable with the recovered 1830s dockyard data than that from other nearby sites, which is reflected in lower levelling uncertainties. Fortunately, a number of stable bench marks around the Plymouth Devonport Dockyard still exist. The 1833 to 1838 MTLs for Plymouth are recorded in Whewell (1839). The published 1833 and 1834 MTLs agree with our estimates to within 3mm. Salcombe (1856) appears to be an outlier, whilst Dartmouth and Fowey are consistently high in both 19th and 20th Centuries, suggesting a real modern difference, either from ODN levelling or hydrodynamic differences.

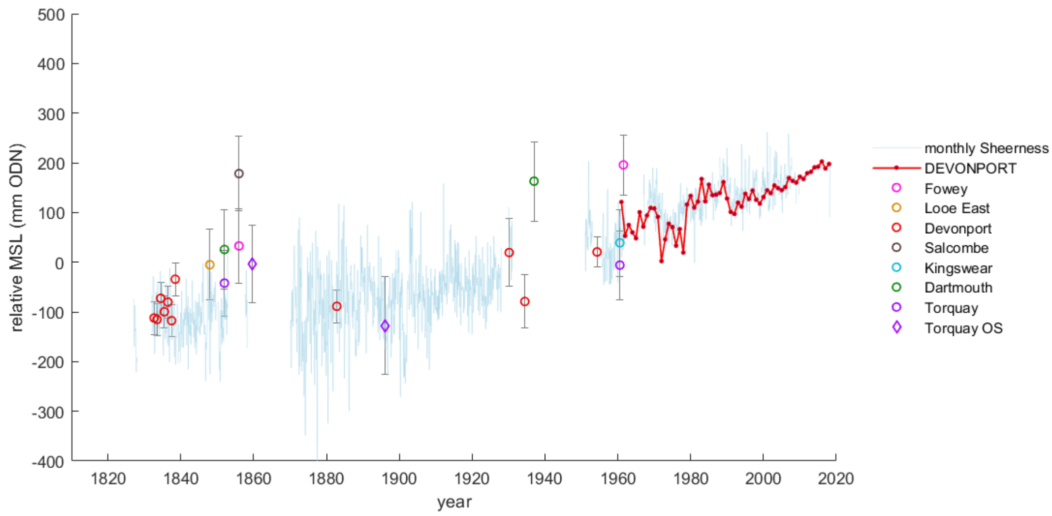


Figure 5.14: Plot of Plymouth (Devonport) data cluster, overlaid on the monthly Sheerness data.

5.5.4. Milford Haven, cluster AD.

This is an extensive harbour, with sea level measurements over several years, made at four separate locations from 1832 to 2018 (Fig 5.15).

The Admiralty Dockyard (Pembroke Docks) measurements digitised here extend from November 1832 to December 1834. Another set of observations between 1886 and 1892 (from 1 km across the River Cleddau at Neyland) are given in Thompson (1915) in feet above local ODL at that time. The St Anne's Head level from 1894 fits well, but the larger uncertainties reflect levelling to the remote location. The PSMSL has data from Newton Noyes 1964 to 1980, and Hakin from 1987 to 2018. The Pembroke Dock measurements are not to the same precision as at the other three Dockyards in the 1830s, as several Low Waters are given to the nearest foot, and sometimes on extreme low tides, the gauge dries out with levels given as "mud". The computed values for MTL omit these Low Waters (and the adjacent High Waters to avoid bias). The majority of the other values are given to the nearest 3 inches. Nevertheless the large number of observations will reduce the uncertainty over each month or year, assuming otherwise random error processes.

There is ambiguity in the ODL and ODN tide gauge bench mark elevations for Pembroke Dock. The 1841 FGL levelling gives an elevation of 14.634 ft above ODL for the Western Camber bench mark, and the stone scale TGZ as 11.864 ft below ODL. Thus the TGZ was 26.498 ft below the bench mark (the Tidal Ledger value gives 26.5 ft). The bench mark elevation was revised to 15.1 ft ODL in the 1860s, but subsequently does not follow the same pattern of elevation changes as for 40 nearby marks through the 1906 revisions to ODL and later to ODN (all reduced back close to the 1841 values), and in 1953 was levelled at 15.15 ft. It is assumed that the tidal observations published in 1833 were referenced to the zero of the same tide gauge carved in the stone wall of the Camber. Here we assume the ODL to ODN adjustments are represented by the mean of changes in 11 pairs of bench mark elevation differences between 1841 and 1970 (standard deviation of 14mm) for the data from the 1832 to 1834 tide register, and use the 1860s levelling for the averaged 1835 to 1838 values reported by the OS. A possible explanation for the rogue elevation is that the joints between granite stonework in the dock wall have expanded, a phenomenon observed elsewhere with similar dock construction methods (Freeman 1903, Talke et al. 2018). Neyland, on the other side of the Cleddau has a mean difference of 82 mm between the revised ODL from the 1860s (in use when the observations were recorded in the 1880s) and ODN. The Neyland MTL values are in PSMSL but only as local Metric data. Here we show this data can be fitted into a wider area context. The PSMSL also have later RLR records from Milford Haven (Newton Noyes (red) and Hakin), either side of Milford Dock, these sites already have modern connections to ODN.

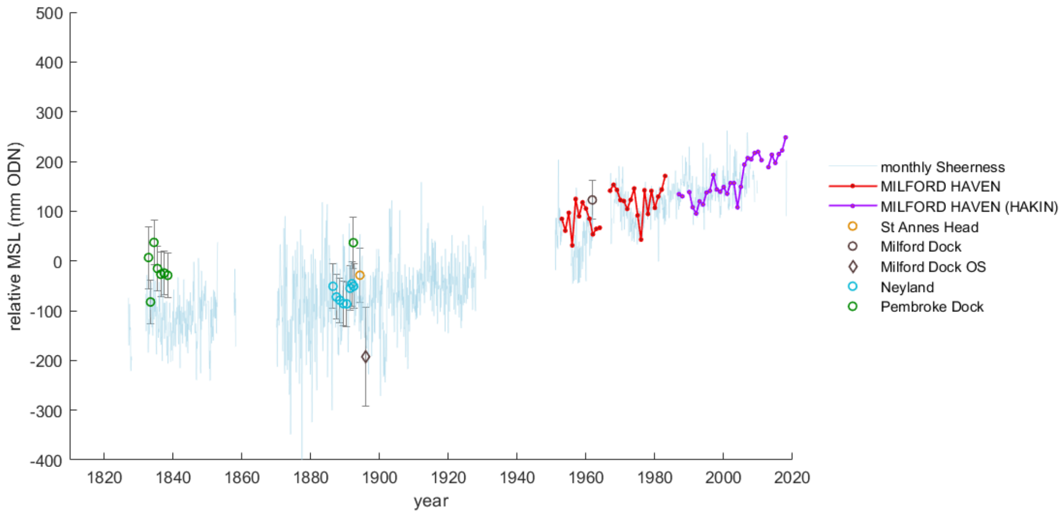


Figure 5.15: Plot of data cluster for Milford Haven, overlaid on the monthly Sheerness data.

5.5.5. Comparing results from all sites

These 4 and the other 32 cluster sites and new data sources are all listed in Table S5.4. As well as data from Admiralty sources, we include: all data digitised from 19th and 20th Century scientific publications, data where new datum information from Admiralty Ledgers has allowed PSMSL "metric" data to be incorporated, and values given in historical Civil Engineering documents. In short we have tried to use all possible data where datum information can also be recovered.

Overall the newly assembled digitised data consists of 508 data points, the equivalent of at least 3322 station-months or 277 station-years. A minority of sites record the year of observation, but no dates; if these are assumed to be a typical 1 month minimum, the total increases to 3348 station months. Of these, 456 of the new sites and associated time periods have no equivalent station-month values for any site in the PSMSL, giving more than 2916 unique new station-month values.

We then derive weighted linear and quadratic trends from the time series and estimate standard errors for:

1) PSMSL RLR annual data for each cluster core site over the length of each series.
2) The extended MER annual mean dataset for each cluster core site which has also been optimally adjusted for datum steps (Hogarth et al. 2020), over the length of each MER series.
3) The full historic data set for each cluster including MER data, over the full span of each series.

A small number of data points (8) have been classified as outliers from examination of the cluster plots. These are discussed in section 5.5.6. These data points are given zero weighting in the final cluster SLR calculations, and are represented by a zero in the final column (column 30) in Table S5.4.

The results for each cluster including MER data and all new data points, adjusted using GIA values from Peltier ICE-6G_C (VM5a) are tabulated in table S5.4 in the supplementary material. We assume GIA to be constant over the 200 years, although we note that the modelled rates for GB systematically vary by typically 0.01mm/yr over periods of 500 years. Fig. 5.16 summarises the results for SLR illustrating the increased alignment of trend values.

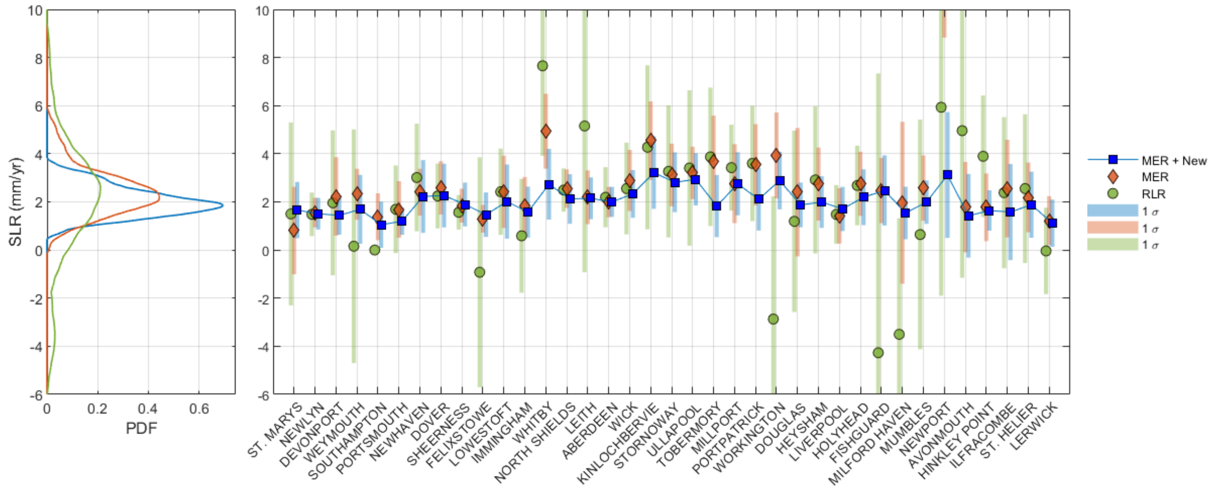


Figure 5.16: Right: plot of linear trends (adjusted for GIA) for the primary cluster sites with uncertainties. Green is the original PSMSL RLR data, Red is the extended PSMSL MER data, and blue is the fully extended MER data as well as all new data points. Left: PDF of the same data over the full length of each data series.

The weighted average linear and acceleration (twice the quadratic coefficient) trends for all clusters (weights based on the inverse of the square of the standard errors in each trend) are summarised in Table 5.2. The weighted average values differ slightly from the peak pdf values in Fig. 5.16 due to the relative weighting. The linear and quadratic trends are fitted simultaneously, and the reference year t_0 for the linear trends is 1915 (Hogarth et al. 2020).

	PSMSL RLR		MER		All data	
	SLR	**SD**	**SLR**	**SD**	**SLR**	**SD**
36 clusters (35 for RLR)	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr
Weighted mean inc. GIA	1.94	0.77	2.04	0.62	1.81	0.41
	SLA	**SD**	**SLA**	**SD**	**SLA**	**SD**
36 clusters (35 for RLR)	mm/yr^2	mm/yr^2	mm/yr^2	mm/yr^2	mm/yr^2	mm/yr^2
Weighted mean	0.014	0.025	0.016	0.015	0.013	0.008
Unweighted	0.173	0.735	0.020	0.072	0.014	0.010

Table 5.2: Weighted average of all 36 cluster SLR trends (adjusted for GIA), and SLA trends with and without weighting. Southampton is not included in the RLR estimates as the PSMSL data is Metric only.

Although the impact of adding the new data depends to some extent on the associated uncertainties, which in some cases can appear relatively high, it is likely that this is outweighed by the number of additional points. The reduction in the average standard deviation of SLR from 0.77 mm/yr to 0.41 mm/yr, suggests that adding the new data improves confidence in the estimates of sea level trends. It is also possible that this reduction is related to the increased effective length of the time series (Zervas 2001). Extending the data set by a century is at least as effective as resolving datum errors in the existing dataset in terms of reducing trend differences. For sea level acceleration, (SLA) the improvements are even more marked. This is discussed further in section 5.6.1. A PDF of computed acceleration values for all cluster sites is given in the supplementary Fig. 5.2s. available at https://www.sciencedirect.com/science/article/pii/S0079661121000112

Applying GIA adjustments from Peltier ICE-6G_C (VM5a) only has a minimal effect on the interstation variability or SE, a point noted in Simon et al. (2018) for Northern Europe as a whole. This will be explored further in section 5.6.

5.5.6 Outliers.

The outliers in the individual cluster plots are explicable in many cases, for example some sites upriver from estuaries such as Cardigan and Appledore have consistently higher MSL values than those of nearby open coast sites with contemporary data. For Liverpool the values for 1868 (and 1872 in the RLR data) are anomalously high, possibly due to the St. Georges floating landing stage (which at that time acted as the float of the tide gauge) grounding on sand which was accumulating under one end of the stage during this period (Le Mesurier 1887). For Barry Island the value for 1861 was recorded before the dock was built, so the dock gauge zero and chart datum must have been applied retrospectively (by comparison). Bunt rejected the first Axmouth value he recorded for 1838, noting it was observed inside the bar at the entrance to the river. Upon investigation the values for Salcombe 1856, Inverness 1837, Portland 1896, and Maryport 1875 also have suspected datum issues and are also treated as outliers. A few other points appear problematic, but without evidence are not treated as outliers here, e.g. the average of the month of observations from Berwick for 1932 appears low. The original datum point for Lerwick (1878) appears relatively high, this may be related to uncertainties in the GIA model (and hence SLR) resulting in an unaccounted vertical offset accumulating over almost a century, but could also be linked to the probable transfer of the datum from Heogan across Bressay Sound at an early date.

The small number of suspect data points (see Fig. 5.19) are given zero weighting in the analysis of the overall trends (Fig 5.16 and Table 5.2). The final cluster trends are our best estimates of the average SLR at each location, again relative to local bench marks. The weighted mean SLR of all clusters is 1.81 mm/year with a weighted standard deviation of 0.41 mm/year.

Obviously we are deriving trends from differing record lengths, and estimating trends from sparse irregularly sampled data is problematic. However the extension of time series at all sites, even when numbers of additional data points are small, reduces the spread of trend values. The mean SLR is also reduced as the average series centre time is moved back in time. This would be expected if there was a common century scale acceleration component underlying all time series and the series were lengthened.

5.5.7 Changes in MSL over 200 years around the British Isles: aggregating cluster results.

We then estimate the vertical ODN offsets between different clusters by simultaneously solving for mean vertical offset differences between the corrected and adjusted cluster MER MSL records using least squares (accounting for gaps and different start/end times). For a number of sites where more than one MER series is included in a cluster we also estimated the MSL referenced ODN offsets for these secondary sites. The difference between core and secondary site offsets is usually small, (cm scale; Fig. 5.17). The next step was to apply these offset values to all newly recovered data within each cluster based on distance from the nearest MER site. Where a new data point site is closer to a secondary MER site than the core MER site, the secondary offset value was applied to the nearest new data points in preference. We make exceptions for data from the PSMSL sites identified in Hogarth (2020) as suspect due to possible subsidence (Newport and the Whitby) which would otherwise bias the mean offset difference. This refinement (introducing an additional 22 PSMSL/MER sites to the 36 core cluster sites which were originally selected) further reduced scatter in the recovered data results, and also accounted for MER sites which appeared to have larger time-averaged MSL differences in periods of temporal overlap than might be expected from the short levelling distance between them (e.g. Shoreham and Newhaven). The final offset values are shown in Fig. 5.17. The PSMSL id. number of the reference site used to derive the offset value for each new site and the distance between them is listed in columns 15 and 16 of Table S5.4 respectively, whilst the offsets are listed in column 25.

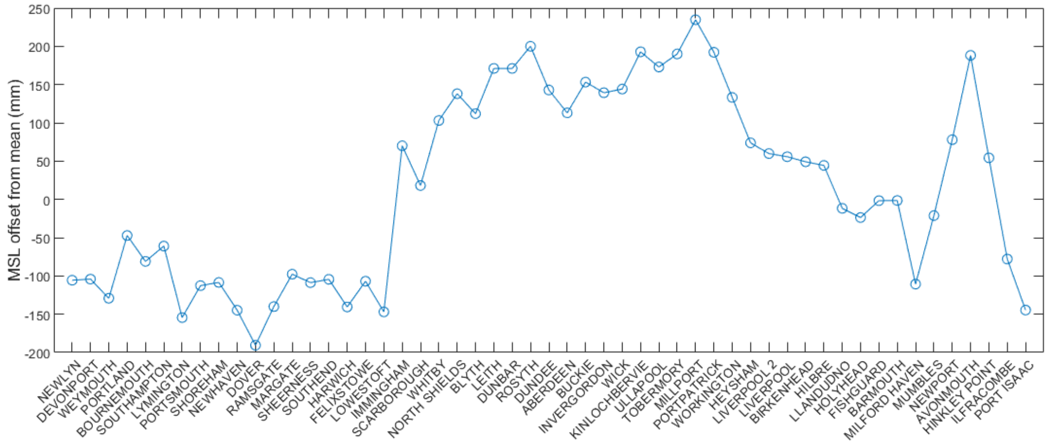


Figure 5.17: plot of offsets applied to all MER cluster and secondary sites used, determined from least squares. These include any ODN levelling errors, and site to site differences show that most adjacent sites have similar ODN related MSL levels, with exceptions across the Wash and for the Severn estuary. Island sites are not represented here.

The aim is to reduce the data in each cluster to a common MSL related datum, assuming any site to site MSL datum differences are due to a) long range levelling errors (Penna et al. 2013) and b) any constant (in time) dynamic topography differences between sites, which may be real, but prevent distant sites from being combined into a single time series.

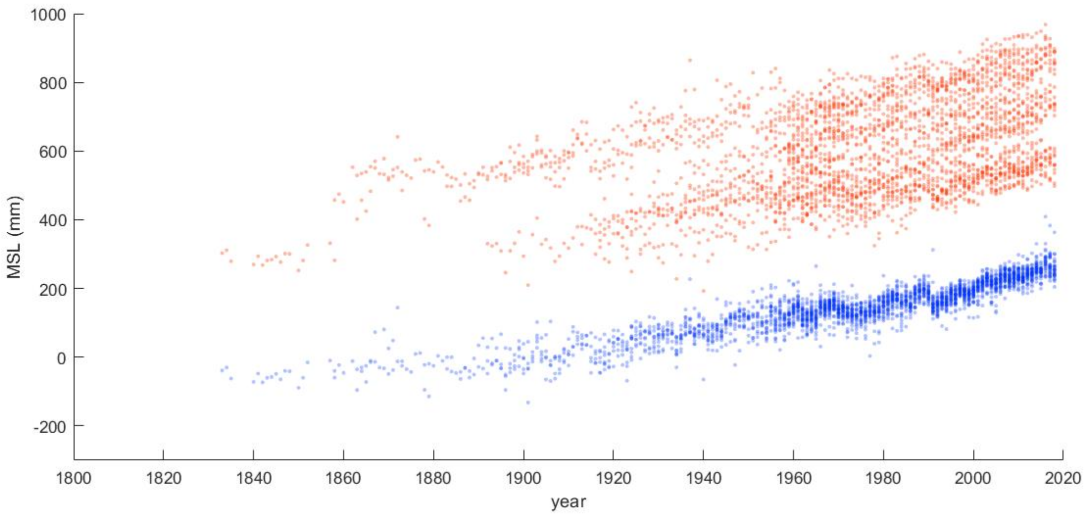


Figure 5.18: Plot of all MER annual data, red: top, reduced to ODN with a centre date of the levelling of the OS fundamental bench marks. Blue: bottom, the same data reduced to a common MSL datum by subtracting the offsets from the common mode (or cluster offsets)

as above. The top plot is offset by 400mm for clarity. Optical density is used to indicate data point overlap.

Fig. 5.18 shows the effect of applying these offsets to the MER ODN referenced annual MSL data (red) with the site (cluster) offsets from the MER common mode subtracted (blue). The MER data has meteorological variability minimised using the methodology described in section 5.4.5 and estimated datum steps removed as in Hogarth (2020). The small number of outliers in individual time series are dealt with in a similar way to the PSMSL RLR data. The spread of data values has been reduced to the point that the common mode signal and variability are now clearly visible over most of the 20th Century.

We now apply the appropriate cluster offsets to the newly assimilated data points in each cluster. These offsets, derived purely from comparing the MER data series, are the only connection between the MER data and the new independent data points.

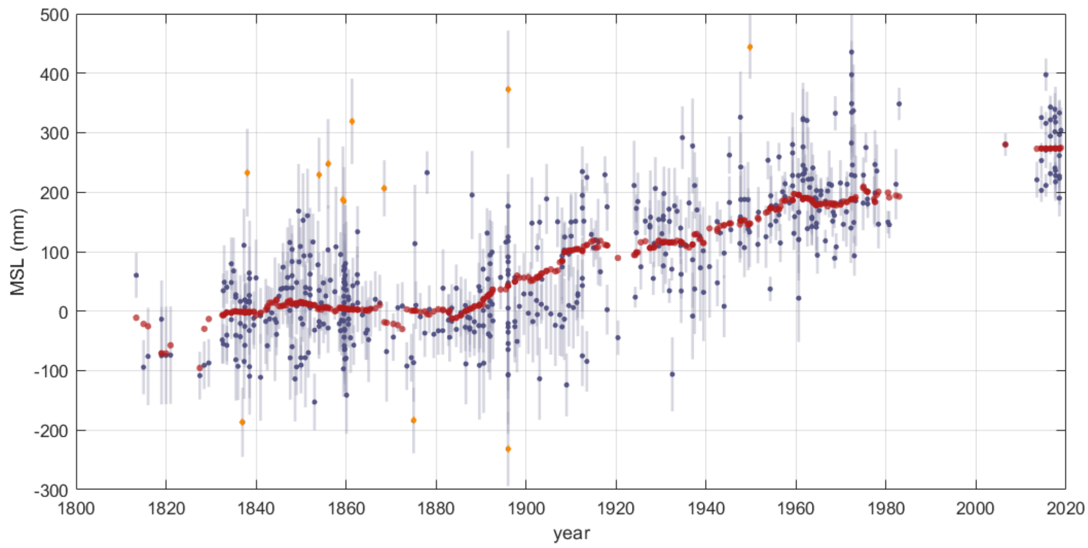


Figure 5.19: Plot showing only the new data points (blue, with outliers as orange diamonds) and uncertainty bars (grey), once offsets independently derived from the nearest MER sites have been applied. The small number of outliers do not contribute to the five year running weighted mean, shown in red.

Compared with pre-adjusted data, this again greatly reduces the spread of MSL values between clusters (Fig. 5.19), the standard error of derived linear trend reduces from 0.138 to 0.081 mm/year. This would be expected if local variability due to meteorological effects has been accounted for and any remaining dynamic interannual or longer period variability due to far ocean effects is common to all sites.

We can then independently estimate (using new data only) how the average MSL for the British Isles has varied over a 200 year period, for example here by using a five year running weighted average (red broken trace in Fig. 5.19).

Comparing with Fig. 5.18, the long-term MSL variation looks similar, but the density of new early data is greatly increased. The gap between the 1980s and 2000s is because IHO data points for this period are annual or multi-year MSL averages extracted from the same tide gauge network which contributes to the annual GB PSMSL records (i.e. they are not independent).

The MER data (blue) is again shown in Fig. 5.20, overlaid onto the new points (red). The annual common mode using the MER data is shown here as a solid blue line, whilst the red broken line is the independent 5-year running average for the new data alone. The only use of MER data in constructing the latter line is to estimate the site-dependent time-mean vertical offsets for each cluster, as shown in Fig. 5.17. For each cluster, the difference between early and later new data is independent of the PSMSL data.

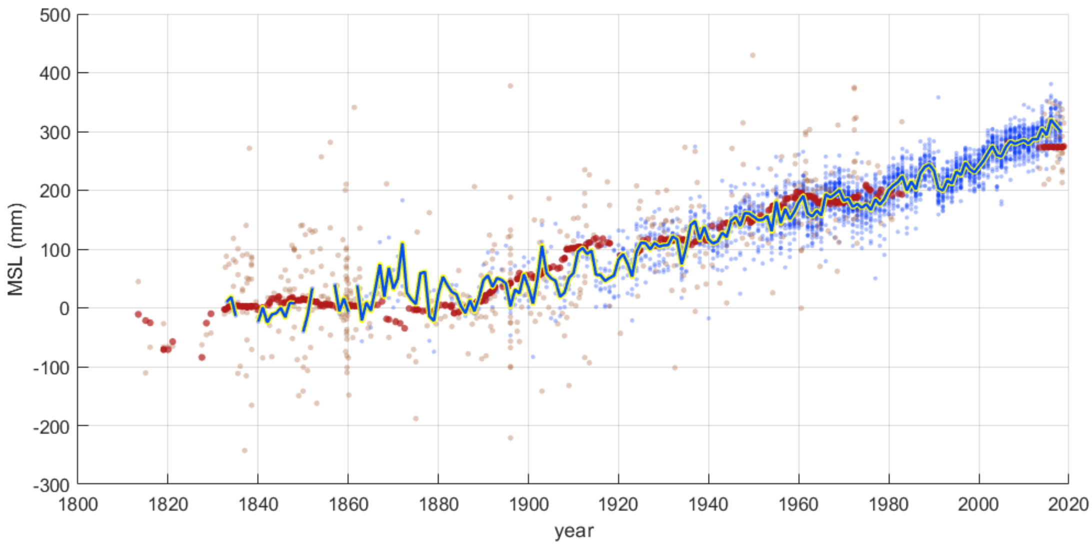


Figure 5.20: The MER data (blue) and new recovered data (red) plotted with the same cluster offsets applied. The red trend line is the 5 year running mean of the new data. The blue line is the common mode derived from the extended annual PSMSL data only.

All existing and new data points have now been systematically reduced as far as possible to a single datum level. This allows an annual weighted average sea level curve and uncertainties to be estimated for Great Britain over the entire period using all available data. The result is shown in Fig. 5.21, where uncertainties in grey are error estimates for years in which there are multiple sites contributing (weighted by the inverse of the estimated errors for each contributing site). Uncertainties in red are the estimated errors accounting for levelling, MTL/MSL and seasonal adjustments where only a single station has contributed.

We now investigate the changes in SLR using several methods. We derive SLR and second order SLA trends for the newly combined annual time series, accounting for the possible effect of coloured (temporally correlated) noise in the MSL signal by using a MATLAB version of the Create and Analyse Time Series (CATS) software (Williams 2008). We compare 19th and 20th Century weighted linear trends, and also develop two stick models and a final three stick model based on minimising the difference between model and observations using weighted least squares.

The linear trend (adjusted for GIA) of the time series of weighted annual means is 1.63 mm/year (standard error 0.14 mm/year) based on the centre year of the series. The estimated acceleration over the whole period is 0.010 mm/yr^2 with a standard error of 0.003 mm/yr^2. The linear trend has additional uncertainties associated with the selection of GIA model, discussed in section 5.6.

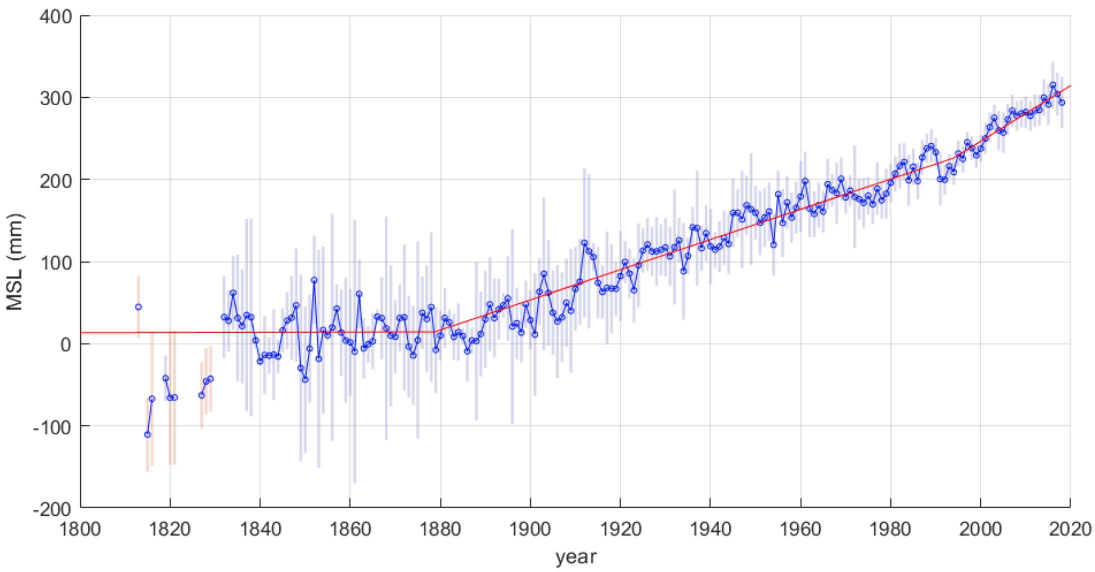


Figure 5.21: Common mode (weighted annual average) of all data points, with uncertainties (blue open circles with lines connecting adjacent years). The grey uncertainty bars represent weighted standard deviation, the red uncertainty bars represent the combined uncertainties for an annual value at a single site. The segmented red line is an optimum piecewise linear trend fit (three stick model).

This estimate of SLA is consistent with previous long term estimates for the British Isles using the PSMSL dataset; for example a SLA of 0.0110 ± 0.0056 mm/year^2 was reported in Woodworth et al. (2009) (NB Woodworth reports the quadratic coefficient, which is half the acceleration). Fig. 5.22 shows that while the addition of a few station-years to the late 20th Century dataset is likely to have minimal impact on the aggregated results, we might expect improvements due to the addition of the large number of data points in the first half of the 19th Century. This can be explored by arbitrarily limiting the analysis to the period before 1900.

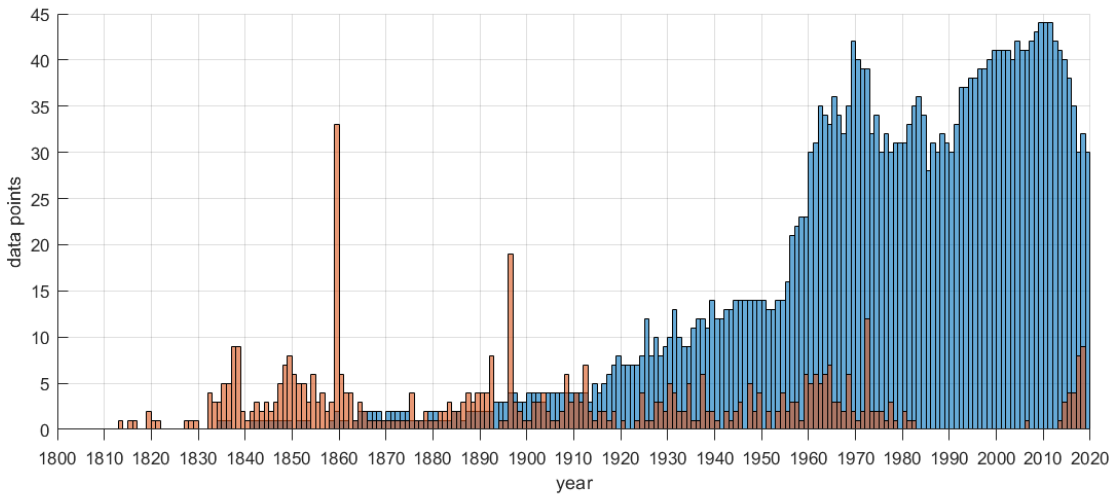


Figure 5.22: Histogram of number of annual PSMSL data points (blue) and new data points (red) showing the increased number of new observations prior to 1900.

We derived weighted least squares estimates of linear trend of the weighted annual means for the 19th Century for:

i. the MER dataset, giving 0.47 mm/yr with a standard error of 0.19 mm/yr using 130 station-years from a limited number of sites.
ii. the new data set, giving an independent value of 0.10 mm/yr with a standard error of 0.19 mm/yr using 268 data points and many more sites.
iii. All data combined, giving 0.24 mm/yr with a standard error of 0.12 mm/yr.

We similarly derived trends for the 20th Century (from 1900 including the early 21st, up to 2018) for:

i. the MER dataset, giving 2.15 mm/yr with a standard error of 0.02 mm/yr using a large number of station years and sites.

ii. the new data set, giving an independent value of 1.86 mm/yr with a standard error of 0.11 mm/yr using a much lower number of station years than the MER dataset (this is likely to be biased low due to the data gap between the early 1980s and the mid 2010s).
iii. All data combined, giving 2.12 mm/yr with a standard error of 0.02 mm/yr.

As the MER or RLR dataset has only one site (Sheerness) pre-1858, there is a possibility of bias in the trend if any GIA or datum related offsets exist between Sheerness and the other RLR sites towards the end of the 19th Century. Importantly, the greater data density and spatial diversity over a longer period of the 19th Century in the new independent dataset gives increased confidence in the conclusion of Woodworth et al. (2009) that for the UK the MSL trend over the 19th Century is significantly lower than over the 20th.

We then explored the timing of a possible change in slope between the 19th and 20th Century SLR using a two stick model, varying the breakpoint for best weighted least squares fit (over all dates). This gave:

i. For the MER dataset, a break point of 1896 (standard error 4 years) with an estimated trend up to this date of 0.39 mm/yr (standard error 0.24 mm/yr), and post break point trend of 2.15 mm/yr (standard error 0.02 mm/yr).
ii. For the new data set, a break point of 1889 (standard error 7.4 years) with an estimated trend up to this date of 0.16 mm/yr (standard error 0.32 mm/yr), and then post break point trend of 2.16 mm/yr (standard error 0.13 mm/yr).
iii. For all of the data combined, a break point of 1888 (standard error 2.9 years) with an estimated trend up to this date of -0.04 mm/yr (standard error 0.17 mm/yr), and then after this date a trend of 2.12 mm/yr (standard error 0.02 mm/yr).

The timing of this break point and relative trend values appear consistent in the independent datasets. This adds further weight to findings of an SLR increase in the late 19th Century in other long Northern European tide gauge records (Woodworth 1990, Wahl et al. 2013). We also note that if a three stick model is used for the MER or combined MER and new data (Fig. 5.21), then the best additional fit breakpoint is in 1994, with an increase in SLR from around 2 mm/yr over the preceding century to 3.4 mm/yr from 1994 to 2018. Although these models (and any long term trend) are oversimplifications of the real long term variability, a three stick model may be more appropriate in this case as, on varying the breakpoint when fitting a two stick model, we find two distinct minima in the weighted variance of residuals, centred around the 1880s and 1990s.

5.6. Discussion

5.6.1. Nonlinearities and acceleration

Whilst there will be uncertainties associated with the assumption that there is an approximate single common mode for the sea level rise rate for Great Britain, this common mode has been shown to be robust since at least 1958. The various causes of datum shifts observed in the modern mechanical tide gauge period (Hogarth et al. 2020) are also likely to affect the earlier fixed gauge observation period. This likelihood is increased for campaign data by the discontinuous nature of observations from temporary gauges (including set up and levelling), contributing to the higher spread in the newly assimilated MSL values. These effects are reduced here by using as many observations as possible in the aggregated results. Deriving trends for individual clusters also requires caution due to the sparse temporal sampling (and lower weighting) of early data compared with more recent data. Although the greater than century scale spans can reduce the impact of any given vertical uncertainties in widely spaced samples, this assumes that large unexpected excursions do not occur in the unsampled sections of time series. Whilst the aggregation of data from multiple sites again helps overcome this and should allow construction of a more representative overall time series, the greater spans will proportionally increase the impact of uncertainties in trend (for example those associated with GIA) on the estimated MSL values.

Although we have computed linear trends for the aggregated RLR and MER data for comparative purposes, Fig. 5.20 indicates that a linear trend at two century scale is not a representative model for sea level variation around the British Isles. There is a marked increase in slope over the recording period. We can test this by fitting a quadratic curve to the data, allowing quantification and comparison with results of previous studies. Although this can be problematic with sparse data, when a weighted second order trend is fitted to each of the individual cluster plots, 33 out of 36 show an increase in the rate of SLR between the start and end of the observation period, with a mean acceleration of 0.014 ± 0.005 mm/yr^2, similar to that derived for the handful of long UK PSMSL series (Woodworth 1999, Woodworth et al. 2009a). Importantly, when the new data is also reduced to a common datum and aggregated into weighted annual mean values, changes in SLR including acceleration are evident, allowing a second order trend to be independently derived which is almost identical to that from the MER series. This long term acceleration in sea level is not steady, but appears to show two decadal periods of increase in the rate of SLR, one in the early 20th Century, and a more sustained period from the late 20th Century to now. It is remarkable that this is also seen in global analyses (Dangendorf et al. 2019). These are closely connected to the resultant break point times and segment trends of the simple three stick model shown in Fig. 5.20. The relatively high acceleration values found when the time period analysed is limited to 1958 onwards (Hogarth et al. 2020) can be explained by the slowdown in the 1960s and rise in the recent period, which is also evident in global studies (Woodworth et al. 2009b, Frederikse et al. 2020a). Looking at shorter temporal scales, for the aggregated RLR and MER data (Fig. 18), even after adjustment for localised meteorological effects, there are pronounced common mode interannual variations e.g. in 1990/91 (Frederikse et al. 2016). In previous work these interannual variations have been strongly linked to variability in integrated alongshore winds along the boundary of the Eastern Atlantic from the late 19th Century onwards (Calafat et al., 2012; Calafat and Chambers 2013; Roberts et al. 2016, Hermans et al. 2020), and the sea level signal (once local meteorological effects have been adjusted for) has similarly been shown to be highly correlated along the shelf boundary from North Africa all the way to the Arctic Ocean (Hogarth et al. 2020) over at least the last 25 years. Fig. 11 in Calafat et al. (2012) implies that choice of start and end points combined with the decimetre scale interannual perturbations caused by alongshore wind variations will affect short term (decadal scale) coastal sea level trend analyses, and is likely to affect estimates of the timing of apparent change points in SLR along the entire North Eastern Atlantic boundary. Volcanic forcing may also play a part (Gregory et al. 2013), the change points following shortly after the major Krakatoa (Gleckler et al. 2006) and Pinatubo (Nerem et al. 2018) eruptions. Whilst the common mode signals for both the MER and independent new dataset both have least squares best fit change points around 1890, caution is required when assessing any higher temporal resolution variation in the averaged signals, as the improved 19th Century data density (Fig. 5.22) and confidence in datum levels are still much lower than for the late 20th Century data. It is difficult to increase confidence in the interannual variation apparent in the early data by comparison with independent regional tide gauge time series because there are very few sites with continuous data from this period. A comparison of our annual GB common mode with annual PSMSL data for Brest (the latter adjusted for atmospheric pressure and geostrophic winds as described in section 5.4.5, and then both data series detrended) which contains MSL data from 1807 but has a ten year gap between the end of 1835 and the start of 1846, shows higher correlation (0.58) than for any of the individual GB sites correlated with the GB common mode, and also shows slightly higher correlation than that of Brest with the averaged MER dataset. However, the correlation degrades before 1835, implying there may be issues with one or both datasets over this period. We can similarly compare with the long historical series from Amsterdam (van Veen 1945, Spencer et al. 1988) by creating a composite of the Amsterdam annual values with PSMSL data from Den Helder for years after 1925 (Fig. 5.23)

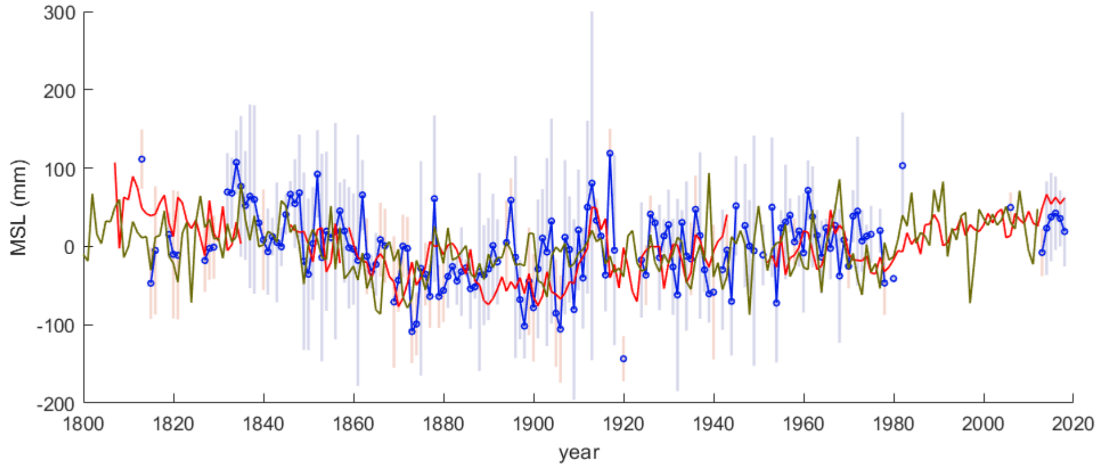


Figure 5.23: Weighted annual means of the new MSL data only (blue with open circle markers) and annual mean values for Brest (red) and Amsterdam/Den Helder composite (green) adjusted for inverse barometer and geostrophic wind (all series linearly detrended). Uncertainty bars for new data only are shown, with colours as in Fig. 5.21.

CATS (Williams 2008) derived estimates of SLR and SLA (accounting for coloured noise) for time series of weighted annual means of the newly assimilated data, existing RLR, extended MER and MER plus the new data are summarised in Table 5.3. The mid-range reference year t_0 (about which the estimated linear trend is centred) is 1915. The standard error values are approximately two to three times larger than those derived from an analysis assuming a white noise model, whilst the effect on trend values is minimal. All trends and accelerations agree to within one standard error, and accelerations are clearly demonstrated at over 2.4 standard errors (> 99% significance level if Gaussian). Using the MER dataset (PSMSL improved and extended using newly-discovered datum information) reduces the errors on the PSMSL estimates, and the new data independently confirm the trend and acceleration seen in these datasets with their limited 19th century sources, while greatly increasing confidence in the 19th century data. The linear trends are lower than the respective averages of the individual SLR cluster values in Fig. 5.16 as the new aggregated times series are now essentially gap free and include all available site-years, effectively increasing the weight of the 19th Century data. This reinforces the conclusion from section 5.5.7 that a linear fit is a poor model for the variation of sea level over the past two centuries. The change in SLR slope between the 19th and 20th Centuries (Gehrels and Woodworth 2013) means that a linear trend will tend to reduce as the time period of analysis is extended back into the 19th Century, so such overall trends should be interpreted cautiously (and with awareness of the GIA model used).

	SLR (mm/yr)	SE (mm/yr)	SLA (mm/yr^2)	SE (mm/yr^2)
Newly recovered data	1.62	0.11	0.010	0.004
PSMSL annual RLR	1.56	0.14	0.012	0.005
MER annual	1.67	0.08	0.013	0.003
All data combined	1.62	0.09	0.010	0.003

Table 5.3: SLR and SLA estimates for the last two centuries derived from time series of annual averages of MSL at all valid sites for: only new data sources, PSMSL RLR data, MER data and finally, the MER data combined with the new data.

5.6.2. Crustal movement

The differences between various GIA models and reference frames has been identified as a major source of uncertainty in regional SLR estimates (Wöppelmann and Marcos 2016, Santamaría-Gómez et al. 2017, Simon and Riva 2020). The longer time series presented in this paper offer further scope for investigation of the GIA component (Valentin 1953), which we have assumed here to be well modelled by the Peltier ICE-6G_C (VM5a) (Peltier et al. 2015; Argus et al. 2014). We see an apparent increase in rates of SLR at higher latitudes after modelled GIA effects have been removed (Fig. 5.16), opposite to that discussed in Woodworth (2018). This is most likely explained by the differences between the Peltier ICE-6G_C (VM5a) and Bradley GIA models (Bradley et al. 2011, Shennan et al. 2012, Shennan et al. 2018) used. We briefly investigated this, finding that using the Bradley model did indeed reduce the link of SLR to latitude, and also gave average SLR figures on average 0.37 mm/yr lower than those reported here using the same MSL data. As expected this made the estimated SLR results more comparable with other UK MSL studies using similar GIA models (Woodworth et al. 2009, Haigh et al. 2009) but this does not alter the main conclusions of this paper about acceleration or relative change in SLR since the 19th Century, which confirm and refine those of previous studies. As any real GIA errors will result in apparent site to site offsets which vary linearly with time, this leads to the suggestion of simultaneously solving for a first order (linear trend) adjustment as well as offset in our array based common mode least squares method.

It is also likely that current mass loss in Greenland is contributing to far field vertical land movement (VLM) in the UK through the elastic VLM response (Kleinherenbrink et al. 2018, Frederikse 2019, Ludwigsen et al. 2020). This would contribute to any differences between modelled GIA and CGPS observation derived VLM. We defer investigation of these factors to future work.

5.7. Conclusions and Future work

Including all the extra historical data summarised in Table S5.4 substantially improves confidence in the local trend estimates. The weighted standard deviation of the cluster trends is reduced on average from 0.103 mm/year to 0.031 mm/year. The aggregated data is extended and densified in the early 19th Century, and increases confidence that the single PSMSL GB record which currently extends into the first half of the 19th Century (Sheerness) is broadly representative of the sea level around the entire GB coast, as well as following similar patterns as other long European records on the Channel and North Sea coasts.

Our best estimate of a single Great Britain MSL rise, after adjusting for vertical land movement is 1.62 mm/year between 1813 and 2018, with a standard error of 0.10 mm/year derived using a mid-range reference year t_0 of 1915 (Hogarth et al. 2020). The estimated acceleration over the whole period is 0.010 mm/yr^2 with a standard error of 0.003 mm/yr^2. These estimates account for the presence of coloured noise, and are likely to be more realistic than using a white noise model, which gives estimates of uncertainties 2 to 3 times lower.

The addition of the newly digitised 1830s Admiralty data for the four Dockyards alone is a major improvement to the UK sea level data set. The new data has been tested against the few earlier publications of the data (Sheerness and Plymouth) and found closely compatible. The connections at ODL and hence ODN would not have been possible without access to the Admiralty Datum Ledgers.

Although of more variable quality, the Tidal Ledger data has also proved extremely valuable. The 1859 OS 15-day sets of data have in general also fitted the cluster trends.

There is, nevertheless, scatter in the final trends as shown in Fig. 5.16. The structure of our analysis allows us to identify ways in which it would be viable to investigate this scatter in detail.

- The conversion from MTL to MSL needs more local sea level measurements and tidal predictions, though in many cases the exact place is not known, and there may have been changes of bathymetry and therefore harmonic constituents of the tidal waveform and thus MTL. These bathymetry changes are often recorded in civil engineering and historical port authority documents, giving scope for model based studies.
- The adjustments for seasonal changes, and for weather effects (wind and air pressures) could be further refined using improved modelling of the sea level changes in the 19th Century. A limitation is that precise observation times for many of the early MSL data are not specified in the information available. Further work could explore the use of historical observational data from individual sites near the tide gauge locations, which is recorded in the tidal ledgers in some cases. Some of these are already assimilated into the 20CRv3 reanalysis.
- Better adjustments for vertical land movements. Longer term measurements using CGPS over more of the UK will in time allow refinement of estimates of GIA and any modern VLM (Hamlington et al. 2016). Although not the focus of this paper we looked at existing CGPS estimates for sparse sites in the UK and confirmed a similar pattern of scatter in trends to using GIA models. The influence of modern mass redistribution will produce VLM and gravity changes which are not linear in time (Frederikse et al. 2019), and is likely to account for some residual signal.
- It is likely, given the detailed work on bench mark comparisons herein, that only modest improvement can be made in this area. However, for some sites where ODL was substantially revised the ODL version used for datum control could be confirmed with more historical metadata. In addition, where doubt exists as to the stability of old tide gauge bench marks, or vertical distance between the bench mark and a fixed tide gauge zero (e.g. on tide scales carved into dock walls), these could be checked by standard levelling or measurement.

This paper shows the importance of rescuing some of the historical sea level data for Great Britain. More generally, there are likely to be similar old tidal records and metadata in other National archives (Caldwell 2012, Hogarth 2014, Wöppelmann et al. 2014, Bradshaw et al. 2015). The UK Admiralty archives alone hold a large amount of well organised information, including data for many non-UK ports assimilated over a long history of global charting and tidal prediction. A program of tide gauge data recovery (similar to that already underway for atmospheric observations) would prove invaluable. Extending the global sea level observational database will allow us to better quantify how sea level has changed and further improve our understanding of the causes (Marcos et al. 2017, Frederikse et al. 2020a).

5.8 Data Availability

Table S5.4 containing the new site MSL data and all adjustments is supplied in document form as well as .csv spreadsheet format in the electronic supplementary material. Additional supplementary material is available which includes Tables S5.1 to S5.5 and a .pdf document containing plots of MSL data for all 36 cluster sites following the format of Fig. 5.12 to 5.15. Also included are .csv spreadsheet files containing the updated extended MER dataset for all UK sites referenced to local ODN as well as the final common mode of GB time series (weighted annual averages of all GB data) derived in this paper. Page images of the majority of the Admiralty Tidal Ledger are contained in supplement 5.2.

Acknowledgements

The Admiralty archives of the Hydrographic Department of the Navy in Taunton, Somerset, are an excellent national facility. It is a pleasure to acknowledge the support and advice we received from the staff during visits, notably, Dr Adrian Webb, Ann-Marie Fitzsimmons and Christopher Jones. In the Admiralty Library Portsmouth, Jenny Wraight, the Admiralty Librarian helped us examine otherwise inaccessible documents in secure areas. Support from the Royal Society librarians is also appreciated. The manuscript benefitted from comments and suggestions from Philip Woodworth, Mattias Green, and the staff of the British Oceanographic Data Centre. Philip also supplied tidal predictions for the 1859 computations, and for many of the conversions from MTL to MSL. The authors are also very grateful to two anonymous reviewers for detailed comments on an earlier version, and for helpful corrections and suggestions which have improved the paper.

The weighted running mean (Fig. 19) MATLAB code is adapted from Greene (2020).

This paper contains work conducted during a PhD study supported by the Natural Environment Research Council (NERC) EAO Doctoral Training Partnership and is fully-funded by NERC whose support is gratefully acknowledged. Grant ref no is NE/L002469/1, UKRI award ref 1950000.

The authors declare that they have no conflicts of interest.

All code used in this research was developed using MATLAB® release 2020a.

MATLAB® is a registered trademark of The MathWorks, Inc., Natick, Massachusetts, United States

Chapter 6: Discussion of results for UK Coastline

6.1 Linear Trends: SLR and the effect of GIA adjustment method

The SLR linear trend for the 1958 to 2018 period and for the 1813 to 2018 period are consistent with several other recent analyses of tide gauge records from the North Sea and German Bight region over similar time periods, but differ from some other UK studies (in effect, the rate is offset, as in Fig. 6.1). This can be reconciled, as the average trend for the UK coastline depends on the choice of GIA adjustment method. In both papers, (chapters 3 and 4 of this thesis) the Peltier GIA model ICE-6G_C (VM5a) was used.

Initial results for overall SLR at each site showed that using a GIA model such as Peltier ICE-6G_C (VM5a) reduced variability in trend values around the GB coastline. In Hogarth et al. (2021), (Chapter 4 of this thesis) it was noted that other GIA models or using CGPS all gave similar reductions in trend variability. Fig. 6.1 gives a plot of the variation of long term SLR linear trend for sites around the UK coastline, where the trends are adjusted for VLM using three methods: 1) the Peltier VLM and geoid correction from ICE-6G (VM5a), 2) a gridded, interpolated and smoothed GPS based solution with additional geoid adjustments from the Peltier model, and 3) the Bradley (2011) GIA model, which already includes geoid corrections. Comparing Fig. 6.1 with Fig 5.16 (note the difference in vertical scale) demonstrates that all of the GIA adjustment methods shown reduce the differences in SLR trend seen around the UK coastline, mainly due to a general north south GIA gradient. We used ICE-6G because it is a global model and would allow regional comparisons without artefacts due to changing from one regional model to another, and the ICE-6G appeared to give the most consistent match to the CGPS data (note the closeness of the PDF peaks near 2mm/yr), which is from a smoothed and interpolated grid derived from a relatively sparse data set (S.D.P. Williams, pers. comm.). Previous publications on UK SLR using the Bradley model to adjust for GIA will show lower overall average trends, and it can be seen that this difference is of a similar order for the majority of sites around the coastline. The average UK trend when site records are corrected with the Peltier model is similar to global results, e.g. 1.64 mm/yr compared to 1.67mm/yr for the latest (Oct. 2020, B. Legresy, pers.comm.) iteration of a GMSL analysis (Church and White 2006, 2011) covering the period 1880 to 2019 (figure 6.2). The GMSL analysis was downloaded (May 2021) from ftp://ftp.csiro.au/legresy/gmsl_files/CSIRO_Recons_gmsl_yr_2019.csv available from the

CSIRO website https://www.cmar.csiro.au/sealevel/sl_hist_few_hundred.html.

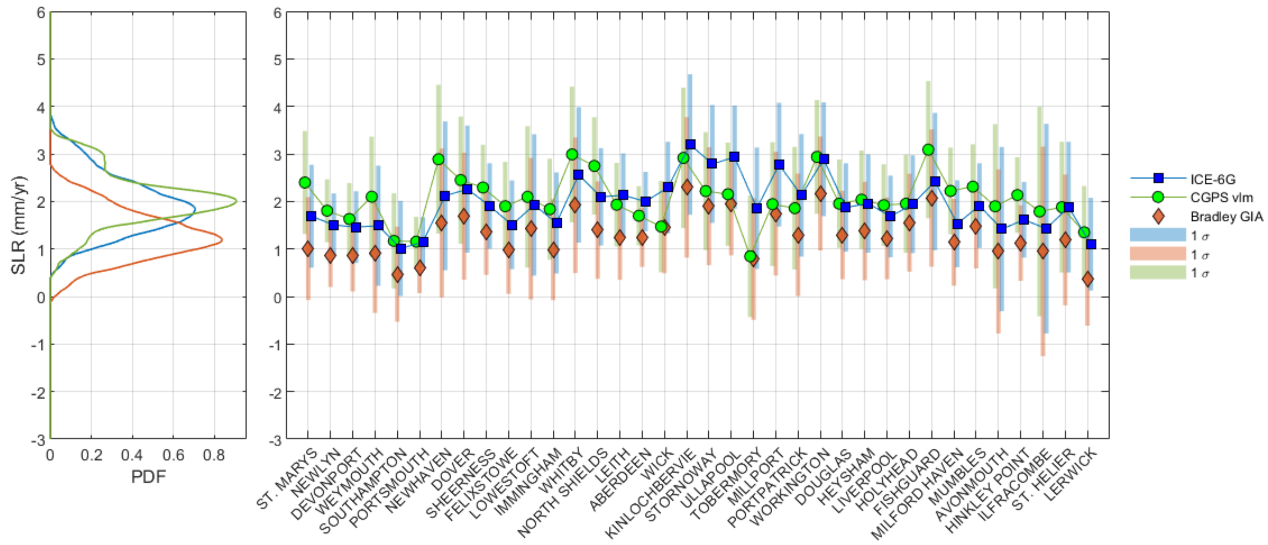


Figure 6.1: Cluster site absolute SLR and PDF of SLR values using different VLM estimates. Blue squares and pdf plot: SLR adjusted using Peltier ICE-6G GIA model. Green circles and pdf plot: SLR adjusted using CGPS derived from interpolated CGPS data. Orange diamonds and pdf plot: SLR adjusted using Bradley GIA model.

The SLR trends derived using GIA adjustments from both the Peltier and the Bradley models show a variation with latitude, seen here as the SLR values being higher in the middle of the right hand plot (northern sites) compared to either end (southern sites, excluding Lerwick). However, unlike the models, using the CGPS adjustment results in almost zero systematic variation with latitude, suggesting an issue with both GIA models which might be investigated in further work.

6.2 Datum steps

An important new result from Chapter 4 is that real datum errors are now identifiable in many of the adjusted time series from UK tide gauges, and these errors continue to arise despite improvements in tide gauge technology and accuracy, as many sources of error are common to all land based gauges (levelling errors, human error, poor maintenance, gauge relocation etc).

These datum errors can be viewed as an additional source of low frequency variability which has been largely unaccounted for, and thus will increase SLR trend uncertainty above that estimated in previous analyses.

These errors are large enough to explain the majority of apparent SLR differences seen between sites within the UK. Such differences could be reconciled by using more realistic uncertainty levels, but this could reduce confidence in records currently viewed as "high quality".

Unlike sea level variations due to far ocean and barotropic influence, the variability due to datum control errors is non-coherent between sites, so can be reduced by averaging results from more than one site (Fig. 3.10b).

These errors are sometimes noticed by the tide gauge operators after comparison with fixed tide scales or other gauges (see appendices), and adjustment is attempted, thus there is a tendency for successive datum changes to have (on average) a more corrective than random or cumulative effect over time.

Most importantly, we show that many of these baseline changes can be quantified where appropriate metadata exists, and thus records can be systematically corrected. This is a more systematic method of attempting to reconcile site to site SLR differences, resulting in improved data quality and reduced uncertainty. A recommendation for operators of modern tide gauges might be to re-introduce systematic repeat levelling at tide gauge sites (particularly after any physical changes such as gauge movement or vessel collision with supporting structures), and to have independent expert review of quality control procedures. For installation of new instruments such as radar gauges, a means of checking and calibrating datum offsets (even when replacing a unit with an identical model) and regularly checking datum stability is essential. Levelling to more than one physical reference point or bench mark, rather than relying on GPS based elevations, will usually also allow connection with historical data, an important factor for long term studies.

6.3 Extension of time series

An important result from Chapter 4 (apart from the crucial addition of new data) is that extending time series to century scale with even a few additional station months of quality controlled data can reduce local SLR trend uncertainty. It is demonstrated that using even small amounts of recovered 19th Century data can have a larger impact on reducing trend uncertainty than adjusting existing shorter time series for known sources of variability.

It is also shown that using the land-based Ordnance Datum as a reference elevation at neighbouring sites, based on an assumption of small levelling errors over short distances, allows a consistent set of composite sea level time series from such sites to be created.

It is further shown that either the Ordnance Datum levelling errors are larger than expected over long distances, or hydrodynamic effects mean that sea level is at different geocentric levels in different parts of the coastline (or both), confirming earlier work by the Ordnance Survey.

If it is assumed that the sea level is consistent around the coastline and components of far field ocean induced variability are common (i.e. mean offset between long term sea level time series is very small), then the records can be superimposed or averaged to create a single consistent UK sea level record with much lower standard deviation between contributing data points from all sites in any given year (or month).

6.4 Acceleration

Both papers (chapters 3 and 4) demonstrate clear acceleration in the UK sea level rise, but averaged over different periods. This acceleration signal, as well as a mid 20th century deceleration signal, are more easily discerned as a result of the methods outlined in this thesis. From the early 19th Century to the early 21st Century an average sea level acceleration of 0.010 ± 0.003 mm/yr^2 is demonstrated in chapter 5. This covers most of the Industrial period. This is statistically significant and is broadly consistent with previous results for the UK, for Europe, and globally using the longest tide gauge time series available. Figure 6.2 shows the GMSL result of the 2019 update from Church and White (2004, 2006, 2011) which is available from: https://www.cmar.csiro.au/sealevel/sl_hist_few_hundred.html with the UK sea level index from this thesis overlaid. This GMSL update was made available after publication of Hogarth et al. (2020) and the derived acceleration value from 1880 to 2019 has increased slightly over the previous update due to the additional years of data to 0.015 ± 0.002 mm/yr^2, although the increase is not significant. Although there are many reasons why regional variability can result in low frequency and interannual excursions away from the global average, the overall annual agreement is within the error bounds from around 1890 onwards. The apparent separation before the late 19th Century (assuming a common datum for the satellite era 1993 to 2019) may be simply due to regional variability (although this raises a question of why this applies only to the 19th Century), or poor quality data biasing the UK record as discussed previously, but it is also possible that this is due to a slight difference in overall linear trend due to the use of different GIA models, as an older GIA model (Davis and Mitrovica 1996) was used in the global reconstruction. The greater than century scale acceleration (independent from any linear GIA differences) derived from a quadratic fit to both series is similar, which could be interpreted as evidence weighing towards this second point, or could indicate errors in the GIA model for the UK. Further adjustments for local geoid changes resulting from currently ongoing loss of land-based ice as well as increased terrestrial freshwater storage from the second half of the 20th Century onwards are possible (Dangendorf et al. 2017). These are likely to introduce more realistic nonlinearities into the UK GIA adjustments (and to an extent for the global Church and White reconstruction also), with a likely small reduction of SLR trends in the earlier sections of record and a small increase in acceleration.

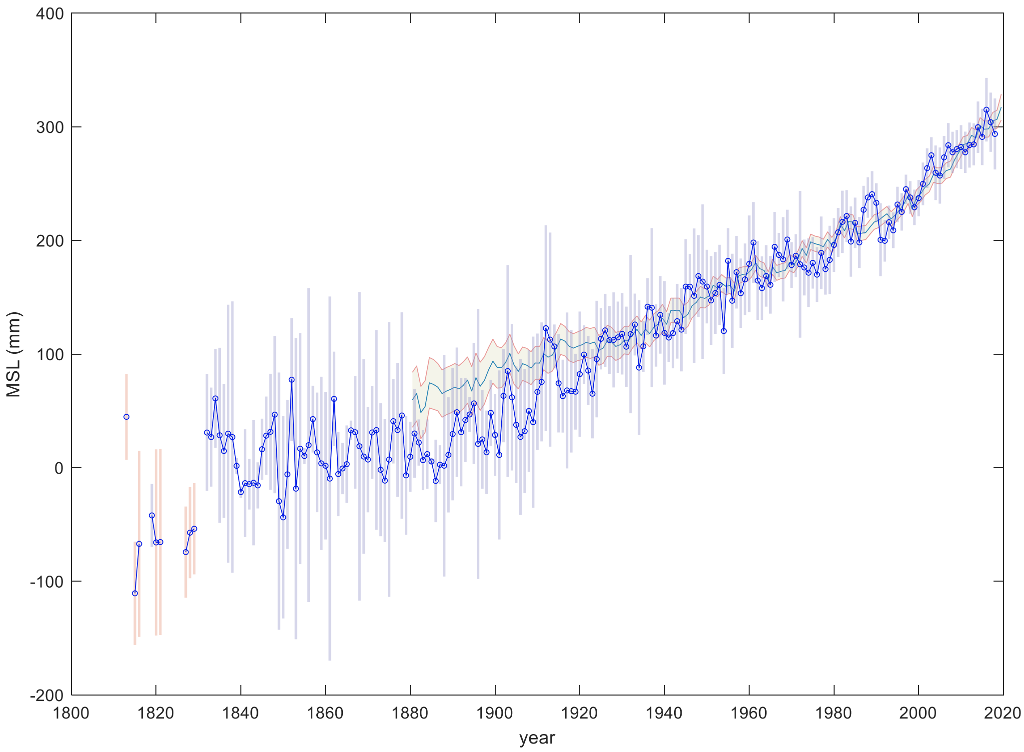


Figure 6.2: The common mode (average) UK SLR result (blue) from this thesis overlaid on the latest (2019) iteration of the Church and White global sea level analysis (green line with light green shaded error bounds, error bound limits shown as red curves).

The change in UK SLR has clearly not been uniform, but for the UK coastline appears to show upwards shifts in trend in the late 19th Century, and again in the late 20th Century.

For the 60 year period 1958 to 2018 the estimated average UK sea level acceleration is 0.056 ± 0.028mm/yr^2. This is four times higher than UK SLA estimated for the overall two century period, but again agrees well with other recent studies covering the UK or North Sea region, as well as the results of the updated (to end of 2019) global analysis from Church and White (2004, 2006, 2011) available from: https://www.cmar.csiro.au/sealevel/sl_hist_few_hundred.html which gives 0.057 ± 0.010 mm/ yr^2 when reanalysed (as part of this research) for the same 1958 to 2018 period, and the results of a hybrid reconstruction of monthly global MSL estimates (reanalysed here for the period 1958 to 2015) from Dangendorf et al. (2019) at https://doi.org//10.1038/s41558-019-0531-8 which also independently gives 0.057 ± 0.010 mm/ yr^2. (N.B. this value is derived here from a simple quadratic fit to the downloaded GMSL reconstruction for consistency, rather than a value derived from the first difference method described in Dangendorf et al. (2019), which gives higher values).

Any second order term (acceleration) is independent of first order variability due to GIA, but is sensitive to short term VLM due to subsidence or local changes in bathymetry at shallow coastal sites (site specific and which will tend to give anomalously high acceleration) or the elastic crustal response to modern glacial melting, models of which indicate an increased land uplift rate in the North of Scotland (Mitroveca et al. 2018) which would lead to a reduction in apparent SLA in affected regions. In the case of the UK as a whole this effect is predicted to add to the ongoing GIA induced North South tilting and affect gauges in Scotland more than the South Coast of England.

It is likely that the major eruptions of Mt Agung (February 1963), El Chichon (April 1982) and Mt. Pinatubo (June 1991), each of which had a transient negative impact on radiative forcing (leading to surface cooling and stratospheric warming) will result in a positive second order component in any ocean heat content changes in the 70 year period 1950 to 2020. This will directly influence global steric sea level. Given that these events were preceded and succeeded by decadal periods of relatively low explosive volcanic activity, this will introduce a non-anthropogenic acceleration component to global SLR over the second half of the 20th Century. This is coupled with impoundment of large volumes of water due to major dam projects undertaken during the 1960s and 1970s, resulting in a permanent transfer of water mass away from the oceans, and a falling sea level component over this period which is unrelated directly to climate but which is anthropogenic. These effects are large enough to introduce a non-GHG related deceleration component to global SLR over the 1930 to 1990 period, but also a non-GHG related acceleration component if the period of analysis is shifted to 1950 to 2010. Any temporary cooling effect due to stratospheric dust load caused by widespread atmospheric testing of nuclear weapons between 1945 and 1980 may also contribute to a reduction in ocean heat content and rate of sea level rise over this period (Fujii 2012), but this has not been as well studied.

Taking these factors into account, it is likely that the significant sea level acceleration observed over the past two centuries underestimates the acceleration that would otherwise have resulted from radiative effects due to accelerating GHG emissions alone over the industrial period, whilst overestimating the acceleration due to the same factor for the 1958 to 2018 period. This suggests that a single long term acceleration value has limited meaning other than to quantify and confirm an overall increase in SLR, and allow comparison between different analyses over similar time periods. These non-climate related components of the sea level budget, if subtracted, produce a smoother rate of change over the 20th Century, but there still remain differences in the timing of changes of rate of SLR between different regional tide gauge records as derived by formal change point methods. These are likely to be due to the influence of natural interannual and decadal timescale fluctuations, which will translate directly into decadal scale variability in the timing of apparent onset of acceleration. The rate of SLR currently observed since 1993 cannot be explained from historical rates and an acceleration component alone, and a sea level budget approach (Frederikse et al. 2020a) should be used, as in the IPCC AR5 and upcoming AR6.

Finally, it is noted that the SLR trend for the UK common mode averaged over the satellite altimetry period (1993 to now) of 3.4 mm/yr is identical to the GIA adjusted result derived from satellite data globally, although again there are many reasons why regional tide gauge records may not necessarily align with global results over periods of a few decades.

6.5 Regional Variability

A somewhat surprising result from Chapter 4 is the wide regional coherence of a residual far field ocean signal once more local weather effects are accounted for, as shown in Fig. 3.23. This is thought to be due to the effects of integrated wind stress driving alongshore (Sturges and Douglas 2011; Calafat et al. 2012, 2013; Roberts et al. 2016) and similar effects have recently been modelled for the North Sea and UK coast (Tinker at al. 2020) where coherence scales of low hundreds of km are exhibited, underpinning our findings (Chapter 4: Hogarth 2020). This long-range coherence due to regional atmosphere and ocean dynamics is important as it can assist in the process of averaging sea level records from individual sites, and identifying datum errors or outlier sites, essentially giving an observational and theoretical basis for the “buddy checking” process.

Chapter 7: Conclusions and recommendations for further work

7.1 Conclusions

The overall aim of this thesis is to extend existing records of mean sea level around the UK coastline, and to develop methods of accounting for the natural variability seen in the UK (and all) tide gauge records. The reason was to better understand the variation in sea level, and to determine whether a climate related signal such as long term acceleration was present. Long term SLR and SLA is confirmed around the entire UK coastline. For sites where recent decadal scale sea level falls have been reported (such as Workington), these are shown to be due to a combination of datum control errors and insufficient record length. Datum shifts due primarily to instrumentation changes have been shown to be a significant error source in many of the UK tide gauge records. Many of these shifts have not been differentiated from assumed inter-site variability due to other causes until now. Accounting for these shifts with recorded calibration data and knowledge of physical changes at the tide gauge allows these errors to be greatly reduced, to the point that inter-site variability and differences in GIA adjusted SLR are much smaller and records appear visually similar. This suggests that other regional records around the world may have similar issues which have yet to be accounted for, and that these could be investigated and potentially corrected using the methods outlined in this thesis. This raises concerns that uncertainties in many tide gauge records globally have been underestimated. It is currently unclear whether historical tide gauge records are more or less likely to suffer from such datum changes, but it is clear that some older records are the result of meticulous record keeping and that levels of maintenance and data quality have varied with time, not always for the better.

Results from previous work showing that variability in regional tide gauge records can be reduced using adjustments for GIA, barotropic effects and far field ocean effects are confirmed. An optimum (to date) method for the UK Coastline is proposed and demonstrated which builds on previous studies. This relies to an extent on the surprisingly extensive coherence of a residual far field ocean signal which emerges once more local weather effects are accounted for. This further allows us to suggest that any large differences seen in historical tide gauge records from locations a few hundred km apart may be due to instrumentation errors in addition to any real sea level variations, so this introduces a note of caution when attempting long term GMSL reconstructions.

The measured relative sea level rise is least in Scotland, and increases moving South, primarily due to long term GIA effects. The geocentric sea level rise since 1958 is of order 2mm/yr using the Peltier ICE-6G (VM5a) GIA model, agreeing closely with the result obtained from tide gauge data adjusted for VLM with smoothed interpolated observations of vertical land movement given by CGPS over the entire UK. A further reduction in spread of site SLR estimates is obtained using the Bradley GIA model compared to the Peltier one, but there is a consistent trend offset of order 1mm/yr. between the Bradley GIA model and CGPS derived values (the Bradley model giving slightly lower SLR).

Acceleration in sea level of 0.010 ± 0.003 mm/yr^2 is confirmed over the two-century period prior to 2018 and is independent of GIA models or linear GIA trends derived from CGPS observations. This acceleration is of similar magnitude to previous results from the UK, but using more data from more sites. It is also of similar magnitude to results derived from the longer term (greater than 120 years) site records globally, or results from global reconstructions which include the long PSMSL records since 1880. However, the observational evidence suggests that the 19th Century sea level was relatively stable around the UK, and thus if the period of analysis stretches back to the 1800s, then overall acceleration estimates will be reduced compared with an analysis starting in 1850 or 1880. Conversely, if the current observed SLR of 3.4 mm/yr continues (even at a constant rate) for another 20 years the overall quadratically derived century scale acceleration will increase to around 0.020 mm/ yr^2.

Larger UK sea level acceleration is seen in the period 1958 to 2018, but as with other regions around the world, there is low acceleration or deceleration in the 60 year period from 1930 to 1990.

That these longer term global and to some extent regional changes can now be reconciled with known drivers, should give increased confidence in projections which more fully account for these factors (Hermans et al. 2020, Nowicki et al. 2020, Woodworth et al. 2021, Hermans et al. 2021) even if the uncertainties associated with some parameters in the latest CMIP6 sea level projections appear to be higher than for CMIP5 (Jevrejeva et al. 2020).

7.2 Datums and bench marks

This work has emphasised the need for a database of bench mark and other metadata for tide gauges which can be added to along with any newly digitised or recovered tide gauge data. Archives relating to local harbour surveys or national mapping campaigns have proved useful previously (Hogarth 2014, Talke 2018). For the UK tide gauges, we have used a simple time series of dates and "events" as well as relative elevation data from National mapping surveys to create an offset file with which to adjust the original tide gauge record, but a universal format for datum connections and correction files needs to be discussed amongst the various groups working on sea level and defined.

7.3 GIA using updated GNSS observations

As discussed in Chapters 4 and 5, the GIA adjustments used from Peltier ICE-6G may not be optimum for the UK coastal sites, and it appears that GNSS observations from the UK now have sufficiently long time series, and quality control has now advanced to the point where a gridded and interpolated CGPS dataset shows similar (if not slightly better) reductions in long term SLR trend differences around the UK coast, with minimal systematic variation due to latitude. As many CGPS records are relatively short, even a few additional years of data could offer improvements and allow better adjustment of tide gauge data for the UK and globally. However, for UK sites, the assumption that modern rates of VLM are adequately simulated by a long term linear GIA component is likely to be inadequate (Dangendorf et al. 2017, Frederikse et al. 2020a), and GNSS observations can only reflect recent land motion, which might include effects due to (for example) the accelerated mass loss from the Greenland Ice Sheet observed since the 1990s. This means that GPS observations may not represent VLM or GIA over the tide gauge recording period. Looking ahead, GNSS observations will directly record any future changes in VLM rate due to the accelerating land-based ice mass loss (Sasgen et al. 2020, Briner et al. 2020). Projecting future SLR is outside the scope of this thesis, but it is noted that the CMIP6 model projections show an increased Greenland ice mass loss rate over CMIP5 as used by the current IPCC projections for sea level rise (Hofer et al. 2020, Payne et al. 2021) whilst very recent research suggests the Greenland Ice sheet may now be becoming unstable (Boers and Rypdal 2021).

7.4 Further work: Extending to Europe, the Baltic, US, Japan, and globally

The sort of metadata and techniques used in this study are applicable to any sea level dataset where metadata or additional sea level data is available, and provide several basic and crucial additional steps and checks on the process which converts high frequency raw observations into quality controlled monthly MSL data as used in climate studies. The records from the Baltic, the coastline of Europe including the Mediterranean, and the Atlantic and Pacific Coastlines of the US all have high quality records with accessible national archival records which might be searched for additional metadata. In addition, sea level data and metadata from many other countries may be uncovered from searches of other archives relating to Naval or Civil Engineering activities. Archives of frequent repeat levelling in Japan exist from the early 20th Century, and might prove invaluable in the efforts to disentangle variations in sea level from seismically induced land motion for this region.

It is also probable that ongoing and future data archaeology exercises will uncover or allow use of further sea level data from around the world, with additional data extensions for existing series.

The case studies presented in this thesis deal with the coastal waters of Great Britain. It has been demonstrated that a long-term acceleration is present regionally, but that this appears to be better represented by a two stick or three stick model than a slowly increasing continuous second order variation. It is noted that trend and acceleration values appear similar to global values when derived over periods of over a century. However, the best fit change point for change in rate of SLR is likely to differ from region to region globally due to the influence of shorter term and more localised decadal and interannual variability. Whilst all sources of regional variability have not been completely eliminated, by systematically adjusting the records the residual regional SLR signals appear to more clearly reflect global long term changes. Whether this is the case for other regions will be the subject of further research.

The realisation that tide gauge reference points exhibit cm scale step changes even in quality controlled data sets is a concern, and methods were developed to mitigate this which proved successful and robust in the case of data from UK tide gauges. It is likely that such errors exist in other regional datasets, and this suggests a careful assessment of the global repository of tide gauge data and metadata might be required if specific time series are to be used to represent regional changes, rather than averaged results from several stations. The techniques adopted would also be useful where known datum shifts have occurred due to seismic events, around the Pacific rim and in particular around the coastline of Japan, where a number of long tide gauge records are available. Additionally, there are several sites around the world where short historical sections of data are available. This thesis (and other work referred to herein) shows that such data can still be assimilated and be useful, provided uncertainties are properly accounted for. This may help fill gaps in our knowledge of sea level change in regions which are currently poorly represented in the global data repositories, such as Africa, South America and the Pacific islands.

Bibliography

Aarup, T., Merrifield, M. A., Pérez, B., Vassie, I., & Woodworth, P. L. (2006). Manual on Sea Level Measurement and Interpretation. Volume IV: An update to 2006. Intergovernmental Oceanographic Commission Manuals and Guides. Paris: Intergovernmental Oceanographic Commission of UNESCO.

Abram, N., Kaufman, D., McGregor, H., Martrat, B., Bothe, O., & Linderholm, H. (2021) Global climate goes regional, and vice versa: reflecting on 14 years of the PaGes 2k Network. https://doi.org/10.22498/pages.29.1.16

Admiralty (1833). Observations of the tides. Communicated to the Royal Society by the Admiralty. Richard Taylor, London.

Admiralty (1839). Observations of tides taken at Her Majesty's Dockyards at Sheerness, Portsmouth, Plymouth and Pembroke. Printed by order of the Lords of the Admiralty. London 1839. Cited in James (1861). We have not been able to find the original publication.

Admiralty (1862) General instructions for the Hydrographic Surveyors of the Admiralty. Potter, London.

Son Ahlmann, H. (1949). Preliminary Glaciological Plans for the Norwegian-British-Swedish Antarctic Expedition, 1949–52. Journal of Glaciology, 1(5), 286-289. doi:10.3189/002214349793702809

Airy, G. B. (1843). VI. On the laws of individual tides at Southampton and at Ipswich. Philosophical Transactions of the Royal Society of London, (133), 45-54.

Airy, G. B. (1845a). On the laws of the tides on the coasts of Ireland, as inferred from an extensive series of observations made in connection with the Ordnance Survey of Ireland. Phil. Trans. R. Soc. 135, 1-124.

Airy, G. B. (1845b). Tides and waves. B. Fellowes.

Allan, R., & Ansell, T. (2006). A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004. Journal of Climate, 19(22), 5816-5842.

Altamimi, Z., Collilieux, X., Métivier, L. (2011). "ITRF2008: an improved solution of the international terrestrial reference frame". Journal of Geodesy. 85 (8): 457–473. Bibcode:2011JGeod..85..457A. doi:10.1007/s00190-011-0444-4

Amante, C. and B. W. Eakins, (2009) ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009. http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/docs/ETOPO1.pdf

Anon (1832) The Tide Gauge at Sheerness. The Nautical Magazine: A Journal of Papers on Subjects Connected with Maritime Affairs, Volume 1. Pp 401-404. Brown, Son and Ferguson, London

Anon (1835) Observations of the tides taken at His Majesty's Dockyards at Sheerness, Portsmouth, Plymouth and Pembroke. Printed by Order of the Lords of the Admiralty. London: Printed by William Clowes. [extension of data in Royal Society (1833), to December 1834].

Anon (1836a) Directions for Observing the Tides. Report of the Fifth Meeting of the British Association for the Advancement of Science, Dublin 1835. Xxxiii-xxxv. J. Murray, London.

Anon (1836b) Tide Gauge Register. West of England Journal of Science of Literature. I, II, III, IV and V. pp 86, 189, 257, 369 (records of HW and some LW from Bristol self registering gauge installed 1833)

Anon (1837) Second Report of the Meteorological Committee of the South African Literary and Scientific Institution. Madras Journal of Literature and Science. No 15, April. Pp 393-399.

Anon (1843) Observations des marées faites à La Mâture et au bassin dans le port de Brest 1807–1835. Bureau des Longitudes, Paris

Anon (1845). Second Report of the Commissioners Appointed By Her Majesty To Inquire into and Consider the most Effectual Means of Improving the Metropolis, and of Providing Increased Facilities of Communication within the Same. 7 May 1845. Appendix 1. Pp 1-245. House of Commons. London.

Anon. (1823) Description of a New Tide Gauge. Art. XVII. Astronomical and Nautical Collections. No. XVI. Quarterly Journal of Science, Literature, and the Arts. No. XXXII. Pg 348. W. Clowes, London.

Anon. (1899) The Effect of a Severn Tidal Wave. The Railway Magazine, Volume 5, pg. 68. Temple Chambers, London

Argus, D.F., Peltier, W.R., Drummond, R. and Moore, A.W. (2014) The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based upon GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories. Geophys. J. Int., 198(1), 537-563, doi:10.1093/gji/ggu140.

Aucan, J., Merrifield, M. A., & Pouvreau, N. (2017). Historical Sea Level in the South Pacific from Rescued Archives, Geodetic Measurements, and Satellite Altimetry. Pure and Applied Geophysics, 174(10), 3813-3823.

Avers, H. G. (1927). A study of the variation of mean sea-level from a level surface. Eos, Transactions American Geophysical Union, 8(1), 56-58.

Baart, F., Van Koningsveld, M., & Stive, M. J. F. (2012). Trends in sea-level trend analysis. Journal of Coastal Research, 28(2), 311-315. https://doi.org/10.2112/JCOASTRES-11A-00024.1

Bailey, F. (1833). Report on the Pendulum Experiments made by the late Henry Foster, R. N., in his Scientific Voyage in the Years 1828-1831, with a View to Determine the Figure of the Earth. Memoirs of the Royal Astronomical Society, Vol. 7, p.1.

Baird, A.W. and Darwin G.H. 1885. Results of the Harmonic Analysis of Tidal Observations. Proc.R.Soc.Lond, 39, 135-207.

Barlow, N. L., Long, A. J., Saher, M. H., Gehrels, W. R., Garnett, M. H., & Scaife, R. G. (2014). Salt-marsh reconstructions of relative sea-level change in the North Atlantic during the last 2000 years. Quaternary Science Reviews, 99, 1-16.

Barnett, R. L., Newton, T. L., Charman, D. J., & Gehrels, W. R. (2017). Salt-marsh testate amoebae as precise and widespread indicators of sea-level change. Earth-Science Reviews, 164, 193-207.

Beardmore, N. (1852). Hydraulic tables. Waterlow.

Beaulieu, C., Chen, J., & Sarmiento, J. L. (2012). Change-point analysis as a tool to detect abrupt climate variations. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1962), 1228-1249.

Becker, M., Karpytchev, M., Davy, M., & Doekes, K. (2009). Impact of a shift in mean on the sea level rise: Application to the tide gauges in the Southern Netherlands. *Continental Shelf Research*, 29(4), 741-749.

Beechey, F. W. (1832). Narrative of a Voyage to the Pacific and Beering's Strait, to co-operate with the Polar Expeditions: performed in His Majesty's Ship Blossom... in the years 1825, 26, 27, 28. With illustrations and maps. Carey & Lea.

Beechey, F. W. (1848). VI. Report of observations made upon the tides in the Irish Sea, and upon the great similarity of tidal phenomena of the Irish and English Channels, and the importance of extending the experiments round the Land's End and up the English Channel. Embodied in a letter to the hydrographer. Philosophical Transactions of the Royal Society of London, (138), 105-116.

Bégat, P. (1839). Traité de géodésie à l'usage des marins. Imprimerie Royale, Paris.

Beulig, H. (1935). The changing sea level. Transactions (Institute of British Geographers), (3), 1-46.

Bevan, B. (1821) Barometric observations. *Philosophical Magazine and Journal*. Vol. 57. Pg 158. Richard and Arthur Taylor, London.

Bevans, B. (1832). XL. Tabular abstract of the results of Capt. Lloyd's leveling from the sea near Sheerness to the river Thames at London Bridge: To the editors of the Philosophical Magazine and Journal. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 1(3), 187-189. DOI:10.1080/14786443208647869

Bevis, T. (Commander R.N.). (1851). Replies to Queries (No, 15). Report of the commissioners appointed to inquire as to the proposal for an Irish Packet Station. pp 97-99. Clowes and Sons (for HM Stationery office)

Bingley, R., Dodson, A., Penna, N., Teferle, N., & Baker, T. (2001). Monitoring the vertical land movement component of changes in mean sea level using GPS: results from tide gauges in the UK. *Journal of Geospatial Engineering*, 3(1), 9-20.

Boers, N., & Rypdal, M. (2021). Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point. Proceedings of the National Academy of Sciences, 118(21). https://doi.org/10.1073/pnas.2024192118

Bogusz, J., Hunegnaw, A., Teferle, F. N., & Klos, A. (2019). Using the Vertical Land Movement estimates from the IGS TIGA combined solution to derive Global Mean Sea Level changes.

Boon, J.D., (2012). Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America. Journal of Coastal Research (2012) 28 (6): 1437–1445. https://doi.org/10.2112/JCOASTRES-D-12-00102.1

Bos, M. S., Williams, S. D. P., Araújo, I. B., & Bastos, L. (2013). The effect of temporal correlated noise on the sea level rate and acceleration uncertainty. Geophysical Journal International, 196(3), 1423-1430.

Bowman, A. W., & Azzalini, A. (1997) Applied Smoothing Techniques for Data Analysis. New York: Oxford University Press Inc.

Bradley, S. L., Milne, G. A., Shennan, I., & Edwards, R. (2011). An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science*, 26(5), 541-552.

Bradshaw, E., Rickards, L., & Aarup, T. (2015). Sea level data archaeology and the global sea level observing system (GLOSS). GeoResJ, 6, 9-16. doi:10.1016/j.grj.2015.02.005.

Bradshaw, E., Woodworth, P. L., Hibbert, A., Bradley, L. J., Pugh, D. T., Fane, C., & Bingley, R. M. (2016). A century of sea level measurements at Newlyn, Southwest England. *Marine Geodesy*, 39(2), 115-140.

Bradshaw, E., Woodworth, P.L., Hibbert, A., Bradley, L.J., Pugh, D.T., Fane, C., Bingley, R.M. (2016) A Century of Sea Level Measurements at Newlyn, SW England. Marine Geodesy, 39 (2). 115-140.10.1080/01490419.2015.1121175

Bradshaw, E., Ferret, Y., Pons, F., Testut, L., & Woodworth, P. (2020). Workshop on sea level data archaeology, Paris, 10-12 March 2020.

Brain, M. J., Kemp, A. C., Hawkes, A. D., Engelhart, S. E., Vane, C. H., Cahill, N., ... & Horton, B. P. (2017). Exploring mechanisms of compaction in salt-marsh sediments using Common Era relative sea-level reconstructions. Quaternary Science Reviews, 167, 96-111.

Briner, J. P., Cuzzone, J. K., Badgeley, J. A., Young, N. E., Steig, E. J., Morlighem, M., ... & Nowicki, S. (2020). Rate of mass loss from the Greenland Ice Sheet will exceed Holocene values this century. Nature, 586(7827), 70-74. https://doi.org/10.1038/s41586-020-2742-6

Brisbane, T. (1825). Table of the rise of the tide at Hobart Town, Van Diemens Land, in April and May 1822 and January 1823. The Edinburgh Journal of Science. Vol 3, (5) Art. 19. Pp 100-107. Blackwood, Edinburgh.

Bromirski, P. D., Miller, A. J., Flick, R. E., & Auad, G. (2011). Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. Journal of Geophysical Research: Oceans, 116(C7). https://doi.org/10.1029/2010JC006759

Brooks, W. A. (1867) Memoir on the River Tyne (Including Plates). Minutes of the Proceedings of the Institution of Civil Engineers 26:1867, 398-420. doi.org/10.1680/imotp.1867.23166

Brugnara, Y., Brönnimann, S., Luterbacher, J., & Rozanov, E. (2013). Influence of the sunspot cycle on the Northern Hemisphere wintertime circulation from long upper-air data sets. Atmospheric chemistry and physics, 13(13), 6275-6288.

Bruns, H. (1878). Die Figur der Erde: Ein Beitrag zur europäischen Gradmessung (Vol. 8). P. Stankiewicz.

Bruyn, H. D. (1900). On the relation of the mean sea level and the height of half-tide. In KNAW, Proceedings (Vol. 2, pp. 1899-1900).

Bunt, T. G. (1867) Discussion of Tide Observations at Bristol. Philosophical Transactions 157: 1–6.

Bureau des Longitudes (1843) Observations des Marées faites à la mâture et au Bassin dans le Port de Brest 1807-1835. Royal Press, Paris.

Burnett, C. & Carmody, M. (1960) Geodetic levelling and mean sea level in Great Britain. Bulletin Géodésique 55(1), 55-58. https://doi.org/10.1007/BF02539497

Calafat, F. M., & Chambers, D. P. (2013). Quantifying recent acceleration in sea level unrelated to internal climate variability. *Geophysical Research Letters*, 40(14), 3661-3666.

Calafat, F. M., Chambers, D. P., & Tsimplis, M. N. (2012). Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea. *Journal of Geophysical Research: Oceans*, 117(C9). doi:10.1029/2012JC008285.

Caldwell, P. (2012). Tide gauge data rescue. Proceedings of The Memory of the World in the Digital age: Digitization and Preservation, 134-149.

Carrère, L., Faugère, Y., & Ablain, M. (2016). Major improvement of altimetry sea level estimations using pressure-derived corrections based on ERA-Interim atmospheric reanalysis. *Ocean Sci*, 12, 825-842.

Cartwright, D. E., & Crease, J. (1963). A comparison of the geodetic reference levels of England and France by means of the sea surface. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 273(1355), 558-580.

Cartwright, D. E. (1972). Secular changes in the oceanic tides at Brest, 1711–1936. Geophysical Journal International, 30(4), 433-449.

Cartwright, D. E. (2000). Tides: A Scientific History. Cambridge University Press. 292 pgs. (reprint of 1998 ed.)

Cartwright, D.E., Woodworth, P.L. and Ray, R.D. (2017). Manuel Johnson's tide record at St. Helena. History of Geo- and Space Sciences, 8, 1-11, doi:10.5194/hgss-8-1-2017.

Caussinus, H., & Mestre, O. (2004). Detection and correction of artificial shifts in climate series. *Journal of the Royal Statistical Society*: Series C (Applied Statistics), 53(3), 405-425. https://doi.org/10.1111/j.1467-9876.2004.05155.x

Cazenave, A., Meyssignac, B., Ablain, M., Balmaseda, M., Bamber, J., Barletta, V., ... & Wouters, B. (2018). Global sea-level budget 1993-present. Earth System Science Data, 10(3), 1551-1590. https://doi.org/10.5194/essd-10-1551-2018

Celsius, A (1743): Anmärkning om vatnets förminskande så i Östersjön som Vesterhafvet. Kongl. Swenska Wetenskaps Academiens Handlingar, 4, 33-50. (see also Ekman 2013)

Chafik, L., Nilsen, J. E. Ø., Dangendorf, S., Reverdin, G., & Frederikse, T. (2019). North Atlantic Ocean Circulation and Decadal Sea Level Change During the Altimetry Era. *Scientific reports*, 9(1), 1041.

Cheng, L., Trenberth, K. E., Fasullo, J., Boyer, T., Abraham, J., & Zhu, J. (2017). Improved estimates of ocean heat content from 1960 to 2015. Science Advances, 3(3), e1601545. DOI: 10.1126/sciadv.1601545

Cheng, L., Abraham, J., Hausfather, Z., & Trenberth, K. E. (2019). How fast are the oceans warming?. Science, 363(6423), 128-129.

Cheng, L., Abraham, J., Trenberth, K. E., Fasullo, J., Boyer, T., Locarnini, R., ... & Zhu, J. (2021). Upper ocean temperatures hit record high in 2020.

Chugh, R. S. (1961). Tides in Hooghly river. Hydrological Sciences Journal, 6(2), 10-26. https://doi.org/10.1080/02626666109493212

Church, J. A., & White, N. J. (2006). A 20th century acceleration in global sea-level rise. Geophysical research letters, 33(1).

Church, J. A., & White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys in geophysics*, 32(4-5), 585-602. https://doi.org/10.1007/s10712-011-9119-1

Cid, A., Camus, P., Castanedo, S., Méndez, F. J., & Medina, R. (2017). Global reconstructed daily surge levels from the 20th Century Reanalysis (1871–2010). Global and Planetary Change, 148, 9-21.

Clarke, A. R., & James, H. (1858). Ordnance Trigonometrical Survey of Great Britain and Ireland: Account of the Observations and Calculations of the Principal Triangulation; and of the Figure, Dimensions and Mean Specific Gravity of the Earth as Derived Therefrom. Plates. Eyre.

Close, C. (1918). The fluctuations of mean sea-level with special reference to those caused by variations in barometric pressure. The Geographical Journal, 52(1), 51-58.

Close C. (1922a). Introduction. The Second Geodetic Levelling of England and Wales 1912-1921. London: HMSO, 62 pp. and plates.

Close C. (1922b). Abstracts of the Primary Lines of the Second Geodetic Levelling in England & Wales by Colonel Sir Charles Close, KBE, CB, CMG, FRS Director-General of the Ordnance Survey. Southampton. London: HMSO.

Close C. (1923). The Levels of Land and Sea: Great Britain. Science Progress in the Twentieth Century Vol. 18, No. 70, pp. 245-256

Colepresse, S. (1668) An account of some observations, made by Mr. Samuel Colepresse at and nigh Plymouth, A. 1667. by way of answer to some of the quæries concerning tydes, propos'd Numb. 17 and 18. Philosophical Transactions. Vol 2, 33. Pp 632-634. https://doi.org/10.1098/rstl.1668.0006

Compo, G. P., Smith, C. A., & Hooper, D. K. (2014, December). Web-based Reanalysis Intercomparison Tools (WRIT): Comparing Reanalyses and Observational data. In AGU Fall Meeting Abstracts (Vol. 2014, pp. NG33A-3822).

Cook, J. (1772) An account of the flowing of the tides in the south sea, as observed on board His Majesty's Bark the Endeavour, by Lieut. J. Cook, commander, in a letter to Nevil Maskelyne, Astronomer Royal, F. R. S. Philosophical Transactions. https://doi.org/10.1098/rstl.1772.0026

Cunningham, D. (1895) The Estuary of the Tay. (Including plate at back of volume). Minutes of the Proceedings of the Institution of Civil Engineers. Volume 120, Issue 1895, pp. 299-313. Part 2. doi.org/10.1680/imotp.1895.19793

Cutts, R. D. (1877). Field-Work of the Triangulation By Richard D. Cutts: United States Coast Survey. Methods, Discussions, and Results. US Government Printing Office.

Daly, R. A. (1920). A recent worldwide sinking of ocean-level. Geological magazine, 57(6), 246-261.

Dangendorf, S., Wahl, T., Mudersbach, C., & Jensen, J. (2013). The seasonal mean sea level cycle in the southeastern North Sea. Journal of Coastal Research, 65(sp2), 1915-1920.

Dangendorf, S., Calafat, F. M., Arns, A., Wahl, T., Haigh, I. D., & Jensen, J. (2014). Mean sea level variability in the North Sea: Processes and implications. *Journal of Geophysical Research: Oceans*, 119(10). https://doi.org/10.1002/2014JC009901

Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C. P., Frederikse, T., & Riva, R. (2017). Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences*, 201616007. https://doi.org/10.1073/pnas.1616007114

Dangendorf, S., C. Hay, F. M. Calafat, M. Marcos, C. G. Piecuch, K. Berk and J. Jensen (2019). Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, 9(9), 705-710. https://doi.org:/10.1038/s41558-019-0531-8.

Dangendorf, S., Frederikse, T., Chafik, L. et al. (2021) Data-driven reconstruction reveals large-scale ocean circulation control on coastal sea level. Nat. Clim. Chang. https://doi.org/10.1038/s41558-021-01046-1

Daniell, J. F. (1826) On the Barometer. The Boston Journal of Philosophy and the Arts. Pp 346-350. Cummings, Hilliard, & Company. Boston, MA.

Darwin, G.H. (1888). Second series of results of the harmonic analysis of Tidal Observations. Proc.R.Soc.Lond, 45, 556-611.

Daussy P (1831) Mémoire sur les Marées des côtes de France. Connaissance des Temps pour l'année 1834. pp 74–87. Bureau des Longitudes, A. Courcier Paris.

Davis, J. L., & Mitrovica, J. X. (1996). Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America. Nature, 379(6563), 331-333.

De la Beche, H., T. (1839) On the Influence of Atmospheric Pressure on the Tidal Waters of Cornwall and Devon. The Edinburgh New Philosophical Journal, Volume 26. Pp 415-419. A. and C. Black, Edinburgh.

De la Beche, H., T. (1851) The Geological Observer. Pg 523. Longman, Brown, Green and Longmans, London.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... & Bechtold, P. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the royal meteorological society, 137(656), 553-597. https://doi.org/10.1002/qj.828

De Havilland, T. F. (1834). Memorandum on the Tides at Madras. The Madras Journal of Literature and Science, Madras Literary Society and Auxiliary of the Royal Asiatic Society. Vol 1. October 1833 to December 1834. Pp 179-182 Vepery Mission Press, Madras

Denham, H. M. (1836). On the survey of the Mersey and the Dee. Report of the Fifth Meeting of the British Association for the Advancement of Science, Dublin 1835. 64-65.

Dhomse, S. S., Mann, G. W., Antuña Marrero, J. C., Shallcross, S. E., Chipperfield, M. P., Carslaw, K. S., ... & Johnson, C. E. (2020). Evaluating the simulated radiative forcings, aerosol properties, and stratospheric warmings from the 1963 Mt Agung, 1982 El Chichón, and 1991 Mt Pinatubo volcanic aerosol clouds. Atmospheric Chemistry and Physics, 20(21), 13627-13654.

Dieng, H. B., Cazenave, A., Meyssignac, B., von Schuckmann, K., & Palanisamy, H. (2017). Sea and land surface temperatures, ocean heat content, Earth's energy imbalance and net radiative forcing over the recent years. International Journal of Climatology, 37, 218-229. https://doi.org/10.1002/joc.4996

Dobson, J. M. (1899). Buenos Ayres Harbour works.(including appendixes and plate at back of volume). In Minutes of the Proceedings (Vol. 138, No. 1899, January, pp. 170-207). Thomas Telford.

Doodson, A. T. (1924). Meteorological Perturbations of Sea-Level and Tides. *Geophysical Journal International*, 1, 124-147.

Douglas, B. C. (1991). Global sea level rise. Journal of Geophysical Research: Oceans, 96(C4), 6981-6992.

Douglas, B. C. (1992). Global sea level acceleration. Journal of Geophysical Research: Oceans, 97(C8), 12699-12706.

Eccles, J. (1901) Details of the tidal observations taken during the period from 1873 to 1892 and a description of the methods of reduction. Account of the Operation of the Great Trigonometrical Survey of India. Vol XVI. Survey of India, Dehra Dun.

Eckley, I. A., Fearnhead, P., & Killick, R. (2011). Analysis of changepoint models. Bayesian Time Series Models, 205-224.

Edge, R. C. (1959). Some considerations arising from the results of the second and third geodetic levellings of England and Wales. Bulletin Géodésique (1946-1975), 52(1), 28-36.

Edmeades, A. (2015) Mean Sea Level Rise at Bristol Port. Technical Report, Bristol Port Company.

Ekman, M. (2003). The world's longest sea level series and a winter oscillation index for northern Europe 1774-2000. Summer Institute for Historical Geophysics.

Ekman, M. (2009). The changing level of the Baltic Sea during 300 years: a clue to understanding the Earth (p. 155). Åland Islands: Summer Institute for Historical Geophysics.

Ekman, M. (2013). An Investigation of Celsius' Pioneering Determination of the Fennoscandian Land Uplift Rate, and of His Mean Sea Level Mark. Summer Institute for Historical Geophysics.

Emery, K. O., & Aubrey, D. G. (1985). Glacial rebound and relative sea levels in Europe from tide-gauge records. Tectonophysics, 120(3-4), 239-255.

Enfield, D. B., & Allen, J. S. (1980). On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America. Journal of Physical Oceanography, 10(4), 557-578.

Epanechnikov, V. A. (1969). Non-parametric estimation of a multivariate probability density. *Theory of Probability & Its Applications*, 14(1), 153-158.

Fairbridge, R. W., & Krebs Jr, O. A. (1962). Sea level and the southern oscillation. Geophysical Journal International, 6(4), 532-545.

Familkhalili, R., & Talke, S. A. (2016). The effect of channel deepening on tides and storm surge: A case study of Wilmington, NC. Geophysical research letters, 43(17), 9138-9147.

Feuerstein, D., Parker, K. H., & Boutelle, M. G. (2009). Practical methods for noise removal: applications to spikes, nonstationary quasi-periodic noise, and baseline drift. *Analytical chemistry*, 81(12), 4987-4994.

Field, W. O. (1956). Some aspects of glaciers and glaciology. Technical Assistant to Chief of Naval Operations for Polar Projects (0P-O3AO).

Findlay, W., H. (1893) Approximate tide-constants for Table Bay and Algoa Bay. Transactions of the South African Philosophical Society. Vol. 5, part 2, pp 253-258.   Murray and St. Leger, Cape Town.

Flather, R. A. (1981). Results from a model of the north east Atlantic relating to the Norwegian Coastal current. In R. Saetre & M. Mork (Eds.), The Norwegian Coastal Current (Vol. 2, pp. 427–458). Bergen University.

Flather, R. A. (2000). Existing operational oceanography. *Coastal Engineering*, 41(1), 13–40. https://doi.org/10.1016/S0378-3839(00)00025-9

Flather, R. A. and Heaps, N. S. (1975). Tidal Computations for Morecambe Bay. *Geophysical Journal International*, 42(2), 489–517. https://doi.org/10.1111/j.1365-246X.1975.tb05874.x

Flowerdew, J., Horsburgh, K., Wilson, C., & Mylne, K. (2010). Development and evaluation of an ensemble forecasting system for coastal storm surges. *Quarterly Journal of the Royal Meteorological Society*, 136(651), 1444–1456. https://doi.org/10.1002/qj.648

Frederikse, T., & Gerkema, T. (2018). Multi-decadal variability in seasonal mean sea level along the North Sea coast. *Ocean Science*, 14(6), 1491-1501.

Frederikse, T., Landerer, F. W., & Caron, L. (2019). The imprints of contemporary mass redistribution on local sea level and vertical land motion observations. Solid Earth, 10(6), 1971-1987.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L. and Wu, Y. H., (2020). The causes of sea-level rise since 1900. Nature, 584(7821), pp.393-397. https://doi.org/10.1038/s41586-020-2591-3

Frederikse, T., Riva, R., Kleinherenbrink, M., Wada, Y., van den Broeke, M., & Marzeion, B. (2016b). Closing the sea level budget on a regional scale: Trends and variability on the Northwestern European continental shelf. *Geophysical research letters*, 43(20), 10-864.

Frederikse, T., Riva, R., Slobbe, C., Broerse, T., & Verlaan, M. (2016a). Estimating decadal variability in sea level from tide gauge records: An application to the North Sea. *Journal of Geophysical Research: Oceans*, 121(3), 1529-1545.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L. and Wu, Y. H. (2020a). The causes of sea-level rise since 1900. Nature, 584(7821), pp.393-397.

Frederikse, T., Buchanan, M.K., Lambert, E. et al. Antarctic Ice Sheet and emission scenario controls on 21st-century extreme sea-level changes. Nat Commun 11, 390 (2020b). https://doi.org/10.1038/s41467-019-14049-6

Fredriksson, C., Martinez, G., Larson, M., & Eellend, B. F. (2018). Using Historical Storms for Flood Risk Management: The 1872 Storm in South Sweden. RCC Perspectives, (3), 11-18.

Freeman, J. R, (1903) Subsidence of Land and Harbour Bottom. Report of the Committee on Charles River Dam, Appendix 20. Boston: State of Massachusetts, pp. 529-572.

Freycinet, L. de (1826) Voyage Autour du Monde. Executé sur les corvettes de J. M. l' Uranie et la Physicienne, pendant les années 1817, 1818, 1819 et 1820. Pillet Aîné, Paris.

Fujii, Y. (2011). The role of atmospheric nuclear explosions on the stagnation of global warming in the mid 20th century. Journal of atmospheric and solar-terrestrial physics, 73(5-6), 643-652.

Fukumori, I., Wang, O., Llovel, W., Fenty, I., & Forget, G. (2015). A near-uniform fluctuation of ocean bottom pressure and sea level across the deep ocean basins of the Arctic Ocean and the Nordic Seas. *Progress in Oceanography*, 134, 152-172. https://doi.org/10.1016/j.pocean.2015.01.013

Gallagher, C., Lund, R., & Robbins, M. (2013). Changepoint detection in climate time series with long-term trends. *Journal of Climate*, 26(14), 4994-5006.

Gehrels, W. R., Dangendorf, S., Barlow, N. L. M., Saher, M. H., Long, A. J., Woodworth, P. L., ... & Berk, K. (2020). A preindustrial sea-level rise hotspot along the Atlantic coast of North America. Geophysical Research Letters, 47(4), e2019GL085814.

Gerlach, M. J., Engelhart, S. E., Kemp, A. C., Moyer, R. P., Smoak, J. M., Bernhardt, C. E., & Cahill, N. (2017). Reconstructing Common Era relative sea-level change on the Gulf Coast of Florida. Marine Geology, 390, 254-269.

Gibson, A. H., Addison, H., Hindmarsh, R. F., Maunsell, G. A. (1938). Correspondence. An Experimental Investigation of the Effect of Bridge-Piers and other Obstructions on the Tidal Levels in an Estuary. Journal of the Institution of Civil Engineers. Volume 9, Issue 8, Oct. 1938. 9(8), pp. 495–500. (Tyne 1930) https://doi.org/10.1680/ijoti.1938.14600

Gil-Alana, L. A., Yaya, O. S., & Shittu, O. I. (2014). Global temperatures and sunspot numbers. Are they related?. Physica A: Statistical Mechanics and its Applications, 396, 42-50.

Gleckler, P. J., AchutaRao, K., Gregory, J. M., Santer, B. D., Taylor, K. E., & Wigley, T. M. L. (2006). Krakatoa lives: The effect of volcanic eruptions on ocean heat content and thermal expansion. Geophysical Research Letters, 33(17). https://doi.org/10.1029/2006GL026771

Golledge, N. R. (2020). Long-term projections of sea-level rise from ice sheets. Wiley Interdisciplinary Reviews: Climate Change, 11(2), e634. https://doi.org/10.1002/wcc.634

Gornitz, V., S. Lebedeff, and J. Hansen (1982) Global sea level trend in the past century. Science, 215, 1611-1614, doi:10.1126/science.215.4540.1611

Gouriou, T., Míguez, B. M., & Wöppelmann, G. (2013). Reconstruction of a two-century long sea level record for the Pertuis d'Antioche (France). Continental Shelf Research, 61, 31-40. https://doi.org/10.1016/j.csr.2013.04.028

Graff, J., & Karunaratne, A. (1980). Accurate reduction of sea level records. The International Hydrographic Review, 57(2).

Graham, J. D. (1838) Report accompanying the map of the extremity of Cape Cod, Massachusetts, executed during portions of the years 1833, 1834, and 1835. Letter from the Secretary of War. Doc 121, pp 2 – 101. United States Congressional Serial Set. (n.d.). United States: U.S. Government Printing Office.

Gregory, J. M., Bi, D., Collier, M. A., Dix, M. R., Hirst, A. C., Hu, A., Huber, M., Knutti, R., Marsland, S. J., Meinshausen, M. and Rashid, H. A., (2013). Climate models without preindustrial volcanic forcing underestimate historical ocean thermal expansion. Geophysical Research Letters, 40(8), pp.1600-1604. https://doi.org/10.1002/grl.50339

Gregory, J. M., Andrews, T., Ceppi, P., Mauritsen, T., & Webb, M. J. (2020). How accurately can the climate sensitivity to CO_2 be estimated from historical climate change?. Climate Dynamics, 54(1), 129-157. https://doi.org/10.1007/s00382-019-04991-y

Grinsted, A., & Christensen, J. H. (2021). The transient sensitivity of sea level rise. Ocean Science, 17(1), 181-186.

Gutenberg, B. (1933). Tilting due to glacial melting. The Journal of Geology, 41(5), 449-467.

Gutenberg, B. (1941). Changes in sea level, postglacial uplift, and mobility of the earth's interior. Bulletin of the Geological Society of America, 52(5), 721-772.

Haigh, I., Nicholls, R., & Wells, N. (2009). Mean sea level trends around the English Channel over the 20th century and their wider context. Continental Shelf Research, 29(17), 2083-2098.

Haigh, I. D., Wahl, T., Rohling, E. J., Price, R. M., Pattiaratchi, C. B., Calafat, F. M., & Dangendorf, S. (2014). Timescales for detecting a significant acceleration in sea level rise. *Nature Communications*, 5, 3635.

Haigh, I. D., Pickering, M. D., Green, J. M., Arbic, B. K., Arns, A., Dangendorf, S., ... & Woodworth, P. L. (2020). The tides they are a-Changin': A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms, and future implications. Reviews of Geophysics, 58(1), e2018RG000636. https://doi.org/10.1029/2018RG000636

Hames D., Reeve D., Marriott M. and Chadwick A. (2004). Effect of Data Quality on the Analysis of Water Levels along the Cumbrian Coastline. IMA International Conference on Flood Risk Assessment. University of Bath. September 2004

Hamlington, B. D., Leben, R. R., Kim, K. Y., Nerem, R. S., Atkinson, L. P., & Thompson, P. R. (2015a). The effect of the El Niño-Southern Oscillation on US regional and coastal sea level. Journal of Geophysical Research: Oceans, 120(6), 3970-3986.

Hamlington, B. D., & Thompson, P. R. (2015b). Considerations for estimating the 20th century trend in global mean sea level. Geophysical Research Letters, 42(10), 4102-4109.

Hamlington, B. D., Thompson, P., Hammond, W. C., Blewitt, G., & Ray, R. D. (2016). Assessing the impact of vertical land motion on twentieth century global mean sea level estimates. Journal of Geophysical Research: Oceans, 121(7), 4980-4993. doi: 10.1002/2016JC011747

Hamlington, B. D., Frederikse, T., Thompson, P. R., Willis, J. K., Nerem, R. S., & Fasullo, J. T. (2020a) Past, Present and Future Pacific Sea Level-Change. Earth's Future, 2020EF001839.

Hamlington, B. D., Frederikse, T., Nerem, R. S., Fasullo, J. T., & Adhikari, S. (2020b). Investigating the acceleration of regional sea level rise during the satellite altimeter era. Geophysical Research Letters, 47(5), e2019GL086528.

Hamlington, B. D., Piecuch, C. G., Reager, J. T., Chandanpurkar, H., Frederikse, T., Nerem, R. S., ... & Cheon, S. H. (2020c). Origin of interannual variability in global mean sea level. Proceedings of the National Academy of Sciences, 117(25), 13983-13990.

Harley, J. B. (1975). Ordnance Survey maps: a descriptive manual. Ordnance Survey.

Harris, R. A. (1898). Manual of tides, Part 1, Introduction and historical treatment of the subject. Manual of tides, Appendix No. 8. US Coast and Geodetic Survey Report for 1897, pp 325-469.

Haughton, S. (1854). The Solar and Lunar diurnal tides on the coasts of Ireland. Trans. R. Irish Academy, 23, 35-139.

Haughton, S. (1865). The semidiurnal tides on the coasts of Ireland. Trans. R. Irish Academy, 24, 195-211 and 253-350.

Hawkshaw, J. (1873) Report by Mr. John Hawkshaw, Superintending Engineer, upon the Completion of the Public Works at Holyhead Harbour. Accounts and Papers of the House of Commons, Volume 58. pp 465-472

Hawley, W. B., Hay, C. C., Mitrovica, J. X., & Kopp, R. E. (2020). A Spatially Variable Time Series of Sea Level Change Due to Artificial Water Impoundment. Earth's Future, e2020EF001497.

Hay, C. C., Morrow, E., Kopp, R. E., & Mitrovica, J. X. (2015). Probabilistic reanalysis of twentieth-century sea-level rise. Nature, 517(7535), 481-484.

Heinkelmann R. (2013). VLBI geodesy: observations, analysis, and results. In: Geodetic sciences – observations, modeling and applications. S. Jin (ed.), InTech open, ISBN 980-953-307-595-7

Henderson, A. (1857). Report upon the effects produced upon the channels of the Mersey by the alterations which, during the last fifty years, have been made in its banks, on the Tides of the present period compared with the tides registered by Mr. Rendel in June 1844. Report of the Twenty Sixth Meeting of the British Association for the Advancement of Science, Cheltenham, August 1856. Pp 44-46. British Association for the Advancement of Science, J. Murray. London.

Henrici, E. O. (1911). Mean Sea-Level. The Geographical Journal, 38(6), 605-606.

Henrici, E. O. (1920). Precise Levelling. Minutes of the Proceedings of the Institution of Civil Engineers (Vol. 209, No. 1920, pp. 116-153). Thomas Telford-ICE Virtual Library.

Hermans, T.H., Le Bars, D., Katsman, C.A., Camargo, C.M., Gerkema, T., Calafat, F.M., Tinker, J. and Slangen, A.B., (2020). Drivers of interannual sea-level variability on the Northwestern European Shelf. Journal of Geophysical Research: Oceans, p.e2020JC016325.

Hermans, T. H., Gregory, J. M., Palmer, M. D., Ringer, M. A., Katsman, C. A., & Slangen, A. B. (2021). Projecting global mean sea-level change using CMIP6 models. Geophysical Research Letters, 48(5), e2020GL092064. https://doi.org/10.1029/2020GL092064

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... & Thépaut, J. N. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999-2049.

Hicks, S. D. (1978). An average geopotential sea level series for the United States. Journal of Geophysical Research: Oceans, 83(C3), 1377-1379.

Hirayama, S. (1911), Results of the Harmonic Analysis of Tidal Observations made at Various Ports of Japan, J. Coll. Sci., 28(7), Imperial University, Tokyo, Japan. https://doi.org/10.15083/00037786

Hofer, S., Lang, C., Amory, C., Kittel, C., Delhasse, A., Tedstone, A., & Fettweis, X. (2020). Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6. Nature communications, 11(1), 1-11. https://doi.org/10.1038/s41467-020-20011-8

Hogarth, P. (2014). Preliminary analysis of acceleration of sea level rise through the twentieth century using extended tide gauge data sets (August 2014). Journal of Geophysical Research: Oceans, 119(11), 7645-7659. https://doi.org/10.1002/2014JC009976
(Supplements and regional bibliography in:
http://www.psmsl.org/products/author_archive/hogarth2014.php

Hogarth, P., Hughes, C. W., Williams, S. D. P., & Wilson, C. (2020). Improved and extended tide gauge records for the British Isles leading to more consistent estimates of sea level rise and acceleration since 1958. Progress in Oceanography, 102333. https://doi.org/10.1016/j.pocean.2020.102333

Hogarth, P., Pugh, D. T., Hughes, C. W., & Williams, S. D. P. (2021). Changes in mean sea level around Great Britain over the past 200 years. Progress in Oceanography, 192, 102521. https://doi.org/10.1016/j.pocean.2021.102521

Holgate, S. J., & Woodworth, P. L. (2004). Evidence for enhanced coastal sea level rise during the 1990s. Geophysical research letters, 31(7).

Holgate, S.J., Matthews, A., Woodworth, P.L., Rickards, L.J., Tamisiea, M.E., Bradshaw, E., Foden, P.R., Gordon, K.M., Jevrejeva, S., and Pugh, J., (2013). New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research*, 29(3), 493-504. https://doi.org/10.2112/JCOASTRES-D-12-00175.1

Houston, J. R., & Dean, R. G. (2011). Sea-level acceleration based on US tide gauges and extensions of previous global-gauge analyses. Journal of Coastal Research, 27(3), 409-417.

Houston, J. R., & Dean, R. G. (2013). Effects of sea-level decadal variability on acceleration and trend difference. Journal of Coastal Research, 29(5), 1062-1072. https://doi.org/10.2112/JCOASTRES-D-12-00238.1

Houston, J. R. (2021). Sea-Level Acceleration: Analysis of the World's High-Quality Tide Gauges. Journal of Coastal Research. ttps://doi.org/10.2112/JCOASTRES-D-20-00101.1

Howard, W. (1828). Report on the Survey of a Canal from the Potomac to Baltimore, Volume 17, Issue 5. (pg 4). B. Edes, Baltimore.

https://cudl.lib.cam.ac.uk/view/MS-RGO-00014-00059/314

Hughes, C. W., & Meredith, M. P. (2006). Coherent sea-level fluctuations along the global continental slope. *Philosophical Transactions of the Royal Society of London A*: Mathematical, Physical and Engineering Sciences, 364(1841), 885-901.

Hughes, C. W., & Williams, S. D. (2010). The color of sea level: Importance of spatial variations in spectral shape for assessing the significance of trends. Journal of Geophysical Research: Oceans, 115(C10).

Hünicke, B., & Zorita, E. (2016). Statistical analysis of the acceleration of Baltic mean sea-level rise, 1900–2012. Frontiers in Marine Science, 3, 125. https://doi.org/10.3389/fmars.2016.00125

Hunter, J., Coleman, R., & Pugh, D. (2003). The sea level at Port Arthur, Tasmania, from 1841 to the present. Geophysical Research Letters, 30(7).

Hutchinson, W. (1791) A Treatise Founded Upon Philosophical and Rational Principles: Towards Establishing Fixed Rules, for the Best Form of Merchant's Ships and also the Management of Them ... by Practical Seamanship. Thomas Billinge, Liverpool.

Hydrographer of the Navy, (1969) Admiralty Manual of Hydrographic Surveying, Vol 2. Chapter 2, Tides and Tidal Streams. N.P. 134 b. The Hydrographer of the Navy, Taunton, Somerset.

IAPO (Proudman, J., Witting, R., Marmer H. A., Nares, J. D., Vignal, J., Committee on Mean Sea-Level and its Variations), (1939). Monthly and Annual Mean Heights of Sea Level up to and including the year 1936. Publication Scientifique No. 5. International Association of Physical Oceanography.

IAPO, International Association for Physical Oceanography (1958). Monthly and Annual mean heights of Sea-Level, 1952 to 1956 and unpublished data from earlier years. Publication Scientifique No. 19.

Irving, D. B., Wijffels, S., & Church, J. A. (2019). Anthropogenic aerosols, greenhouse gases, and the uptake, transport, and storage of excess heat in the climate system. Geophysical Research Letters, 46(9), 4894-4903. https://doi.org/10.1029/2019GL082015

Jacobs, W. C. (1939). Sea level departures on the California coast as related to the dynamics of the atmosphere over the North Pacific Ocean. J. mar. Res, 2, 181-194.

James (1861b). Abstracts of the Principal Lines of Spirit Levelling in Scotland. By Colonel Sir Henry James, Director of the Ordnance Survey. London: Longman, Green, Longman and Roberts.

James, H. (1861a). Abstracts of the principal lines of spirit levelling in England and Wales. Published by the Ordnance Survey. Printed by Eyre and Spottiswoode, London.

Jänicke, L., Ebener, A., Dangendorf, S., Arns, A., Schindelegger, M., Niehüser, S., ... & Jensen, J. (2020). Assessment of tidal range changes in the North Sea from 1958 to 2014. Journal of Geophysical Research: Oceans, e2020JC016456. https://doi.org/10.1029/2020JC016456

Jensen, J., & Müller-Navarra, S. H. (2008). Storm surges on the German Coast. Die Küste, 74 ICCE, (74), 92-124.

Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S., (2006). Nonlinear trends and multiyear cycles in sea level records. Journal of Geophysical Research, 11, C09012, https://doi.org/10.1029/2005JC003229

Jevrejeva, S., Moore, J. C., Grinsted, A., Matthews, A. P., & Spada, G. (2014). Trends and acceleration in global and regional sea levels since 1807. Global and Planetary Change, 113, 11-22.

Jevrejeva, S., Palanisamy, H., & Jackson, L. P. (2020). Global mean thermosteric sea level projections by 2100 in CMIP6 climate models. Environmental Research Letters, 16(1), 014028. https://iopscience.iop.org/article/10.1088/1748-9326/abceea/pdf

Johnson, D. W. (1917). Is the Atlantic Coast Sinking?. Geographical Review, 3(2), 135-139.

Johnson, D., & Winter, E. (1927). Sea-Level Surfaces and the Problem of Coastal Subsidence. Proceedings of the American Philosophical Society, 465-496.

Johnson, G. C., & Lyman, J. M. (2020). Warming trends increasingly dominate global ocean. Nature Climate Change, 10(8), 757-761.

Jolly, H.P.L.G. & Wolff, A.J., (1922). The Second Geodetic Levelling of England and Wales 1912–1921, Ordnance Survey, HMSO.

Jolly, H. L. P. (1939). Supposed land subsidence in the south of England. The Geographical Journal, 93(5), 408-413.

Jones, P. D., Wigley, T. M., & Wright, P. B. (1986). Global temperature variations between 1861 and 1984. Nature, 322(6078), 430-434. https://doi.org/10.1038/322430a0

Kennedy, J. J., Rayner, N. A., Atkinson, C. P., & Killick, R. E. (2019). An ensemble data set of sea surface temperature change from 1850: The Met Office Hadley Centre HadSST. 4.0. 0.0 data set. Journal of Geophysical Research: Atmospheres, 124(14), 7719-7763.

Killick, R., Fearnhead, P., & Eckley, I. A. (2012). Optimal detection of changepoints with a linear computational cost. *Journal of the American Statistical Association*, 107(500), 1590-1598.

Kleinherenbrink, M., Riva, R., & Frederikse, T. (2018). A comparison of methods to estimate vertical land motion trends from GNSS and altimetry at tide gauge stations. Ocean Science, 14(2). https://doi.org/10.5194/os-14-187-2018

Kleinherenbrink, M., Riva, R., & Scharroo, R. (2019). A revised acceleration rate from the altimetry-derived global mean sea level record. Scientific reports, 9(1), 1-6. https://doi.org/10.1038/s41598-019-47340-z

Klos, A., Kusche, J., Fenoglio-Marc, L. et al. (2019). Introducing a vertical land motion model for improving estimates of sea level rates derived from tide gauge records affected by earthquakes. GPS Solut 23, 102 https://doi.org/10.1007/s10291-019-0896-1

Knibbs, G. H. (1888). Fixation of Mean High Water Mark. The Surveyor. v.1-2 1888-1890. Pg 11. Sydney.

Kramer, R. J., He, H., Soden, B. J., Oreopoulos, L., Myhre, G., Forster, P. M., & Smith, C. J. (2021). Observational evidence of increasing global radiative forcing. Geophysical Research Letters, 48(7), e2020GL091585. https://doi.org/10.1029/2020GL091585

Kyd, J. (1833). Tables Exhibiting a Daily Register of the Tides in the River Hoogly at Calcutta from 1805 to 1828 with Observations on the Results thus Obtained. Asiatic Researches or Transactions of the Society of Asia, Vol XVIII, (XVI) pp 259-267. Bengal Military Orphan Press, Calcutta.

la Cour, D. (1913) Quasinivellement : nogle orientirende Undersögelser vedrörende de Danske Vandstandsmaalinger. Publ. fra det Danske Meteorol. Inst., Meddelelser, Nr. 1. Kjobenhavn.

de La Lande, J. (1781). Traité du flux et du reflux de la mer. Vve Desaint.

LaFond, E. C. (1939). Variations of sea level on the Pacific Coast of the United States. J. Mar. Res, 2(1), 17-29.

Lallemand, C., & Prévot, E. (1929). Long Period Variations in the mean sea level on the French Coast. The International Hydrographic Review.

Larsen, C. F., Echelmeyer, K. A., Freymueller, J. T., & Motyka, R. J. (2003). Tide gauge records of uplift along the northern Pacific-North American plate boundary, 1937 to 2001. *Journal of Geophysical Research: Solid Earth*, 108(B4).

Lavielle, M. (2005). Using penalized contrasts for the change-point problem. *Signal processing*, 85(8), 1501-1510.

Lawrence, D. B. (1950). Glacier fluctuation for six centuries in southeastern Alaska and its relation to solar activity. Geographical Review, 40(2), 191-223. Doi: 10.2307/211280

Le Mesurier, W. H. (1887). On the Removal of Sand from Underneath the Liverpool Landing Stage. (Includes Plates). Minutes of the Proceedings of the Institution of Civil Engineers (Vol. 90, No. 1887, pp. 308-318). Thomas Telford-ICE Virtual Library. Doi: 10.1680/imotp.1887.21026

Lempriere (1837-1842) Digitised original Port Arthur tidal data from National Archives of Australia https://recordsearch.naa.gov.au/SearchNRetrieve/Interface/ListingReports/ItemsListing.aspx

Lempriere, T. J., (1840). Meteorological Register kept at Port Arthur, Van Diemen's Land, & Meteorological Register kept at Port Arthur, Van Diemen's Land by Deputy Assistant Commissary General Lempriere from 1st January to 30th September 1839 inclusive. Transactions of the Bombay Geographical Society, from June 1839 to February 1840. Vol III, pp 206-207. American Mission Press, Bombay.

Lennon, G. W. (1968). The evaluation of tide gauge performance through the van de Casteele test. *Cahiers Oceanographiques*, 20, 867– 877.

Lennon, G. W. (1971). Sea level instrumentation, its limitations and the optimisation of the performance of conventional gauges in Great Britain. *The International Hydrographic Review*, 48(2).

Lenz, H. (1873). Fluth und Ebbe des Meeres. Friederichsen & Co., Hamburg

Levitus, S., Antonov, J. I., Boyer, T. P., Locarnini, R. A., Garcia, H. E., & Mishonov, A. V. (2009). Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. Geophysical Research Letters, 36(7). https://doi.org/10.1029/2008GL037155

Leypoldt, H. (1937). The determination of mean sea level. American Journal of Science, 5(196), 296-302. https://doi.org/10.2475/ajs.s5-33.196.296

Li, Y., & Lund, R. (2015). Multiple changepoint detection using metadata. *Journal of Climate*, 28(10), 4199-4216.

Liebmann, B., Dole, R. M., Jones, C., Bladé, I., & Allured, D. (2010). Influence of choice of time period on global surface temperature trend estimates. Bulletin of the American Meteorological Society, 91(11), 1485-1492. https://doi.org/10.1175/2010BAMS3030.1

Lloyd, J. A. (1830). II. Account of levellings carried across the Isthmus of Panamá, to ascertain the relative height of the Pacific Ocean at Panamá and of the Atlantic at the mouth of the river Chagres; accompanied by geographical and topographical notices of the Isthmus. Philosophical Transactions of the Royal Society of London, (120), 59-68.

Lloyd, J. A. (1831). An Account of Operations Carried on for Ascertaining the Difference of Level between the River Thames at London Bridge and the Sea; And Also for Determining the Height above the Level of the Sea, &c. of Intermediate Points Passed Over between Sheerness and London Bridge. Philosophical Transactions of the Royal Society of London, 121, 167-197.

Lomb, N. R. (1976). Least-squares frequency analysis of unequally spaced data. Astrophysics and space science, 39(2), 447-462.

Long, A. J., Barlow, N. L. M., Gehrels, W. R., Saher, M. H., Woodworth, P. L., Scaife, R. G., ... & Cahill, N. (2014). Contrasting records of sea-level change in the eastern and western North Atlantic during the last 300 years. Earth and Planetary Science Letters, 388, 110-122.

Lord, W. (1855). On the results of the self-registering tide gauge. Transactions of the Lancashire and Cheshire Historic Society, 7, 235-237

Love, J. J. (2013). On the insignificance of Herschel's sunspot correlation. Geophysical research letters, 40(16), 4171-4176.

Lubbock, J. W. (1830). XVII. On the tides in the port of London. The Philosophical Magazine, or Annals of Chemistry, Mathematics, Astronomy, Natural History and General Science, 7(38), 124-129.

Lubbock, J. W. (1835). Discussion of tide observations made at Liverpool. Philosophical Transactions of the Royal Society of London, 125, 275-299.

Lubbock, J. W. (1836). Discussion of Tide Observations Made at Liverpool. Philosophical Transactions of the Royal Society of London, 126, 57-73.

Lubbock, J. W. (1837). Note on the fluctuations of the height of high-water due to changes in the atmospheric pressure. In Abstracts of the Papers Printed in the Philosophical Transactions of the Royal Society of London (No. 3, pp. 485-486). December, London: The Royal Society.

Ludwigsen, C., Khan, S. A., Andersen, O. B., & Marzeion, B. (2020). Vertical Land Motion from present-day deglaciation in the wider Arctic (submitted). Preprint doi: 10.1002/essoar.10502890.1

Luterbacher, J., Xoplaki, E., Dietrich, D., Rickli, R., Jacobeit, J., Beck, C., ... & Wanner, H. (2002). Reconstruction of sea level pressure fields over the Eastern North Atlantic and Europe back to 1500. Climate Dynamics, 18(7), 545-561.

Lyell, C. (1835). I. The Bakerian Lecture. On the proofs of a gradual rising of the land certain parts of Sweden. Philosophical transactions of the Royal Society of London, (125), 1-38.

Mackenzie, J. (1879). The Avonmouth Dock (Including Plates at back of Volume). In Minutes of the Proceedings of the Institution of Civil Engineers (Vol. 55, No. 1879, pp. 3-21). Thomas Telford-ICE Virtual Library. https://doi.org/10.1680/imotp.1879.22380

Mackenzie, M. (1749). The State of the Tides in Orkney; By Mr. Murdoch Mackenzie. Philosophical Transactions (1683-1775), 46, 149-160.

Mackie, E., Shuckburgh, E., Jones, D., & Vaughan, D. (2020). How climate change is affecting sea levels. Weather, 75(9), 280-280.

Maclear, T. (1850). Extract of letter from, respecting Cape observatory. Monthly Notices of the Royal Astronomical Society, 11, 41.

Marcos, M., Marzeion, B., Dangendorf, S., Slangen, A.B., Palanisamy, H. and Fenoglio-Marc, L., (2017). Internal variability versus anthropogenic forcing on sea level and its components. In Integrative Study of the Mean Sea Level and Its Components (pp. 337-356). Springer, Cham.

Marcos, M., Puyol, B., Amores, A., Pérez Gómez, B., Fraile, M. Á., & Talke, S. A. (2020). Historical tide gauge sea-level observations in Alicante and Santander (Spain) since the 19th century. Geoscience Data Journal. https://doi.org/10.1002/gdj3.112

Marmer, H. A. (1925). Mean sea level and its variations. Annals of the Association of American Geographers, 15(3), 106-118. https://doi.org/10.2307/208565

Marmer, H. A. (1932). Mean Sea Level and Half-tide Level. The Military Engineer, 24(137), 498-500.

Marmer, H. A. (1948). Is the Atlantic coast sinking? The evidence from the tide. Geographical Review, 38(4), 652-657.

Marmer, H. A. (1949). Sea level changes along the coasts of the United States in recent years. Eos, Transactions American Geophysical Union, 30(2), 201-204.

Marmer, H. A. (1951). Changes in sea level determined from tide observations. Coastal Engineering Proceedings, 1(2), 6.

Maskelyne, N. (1762). Observations on the tides in the Island of St. Helena: in a letter from the Rev. Nevil Maskelyne, A.M. F.R.S. to Thomas Birch, D.D. Secretary to the Royal Society. Philosophical Transactions of the Royal Society, 52, 586-606, doi:10.1098/rstl.1761.0100.

Matthes, F. E. (1936). Report of Committee on Glaciers, 1935–36. Eos, Transactions American Geophysical Union, 17(2), 286-294.

Matthews, A., Bradshaw, E., Gordon, K., Jevrejeva, S., Rickards, L., Tamisiea, M., ... & Woodworth, P. (2016, April). Mean Tide Level Data in the PSMSL Mean Sea Level Dataset. In EGU General Assembly Conference Abstracts (Vol. 18, p. 8447).

Mawdsley, R.J., Haigh, I.D. and Wells, N.C. (2015) Global secular changes in different tidal high water, low water and range levels. Earth Future, 3, 66–81, doi:10.1002/2014EF000282

McCarthy, G. D., Haigh, I. D., Hirschi, J. J. M., Grist, J. P., & Smeed, D. A. (2015). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature*, 521(7553), 508.

Mengel, M., Nauels, A., Rogelj, J. et al. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. Nat Commun 9, 601 (2018). https://doi.org/10.1038/s41467-018-02985-8

Menne, M. J., C. N. Williams, B.E. Gleason, J. J Rennie, and J. H. Lawrimore, 2018: The Global Historical Climatology Network Monthly Temperature Dataset, Version 4. J. Climate, in press. https://doi.org/10.1175/JCLI-D-18-0094.1.

Merrifield, M. A., Merrifield, S. T., & Mitchum, G. T. (2009). An anomalous recent acceleration of global sea level rise. Journal of Climate, 22(21), 5772-5781.

Merrifield, M. A., Thompson, P. R., & Lander, M. (2012). Multidecadal sea level anomalies and trends in the western tropical Pacific. Geophysical Research Letters, 39(13).

Meyssignac, B., Boyer, T., Zhao, Z., Hakuba, M. Z., Landerer, F. W., Stammer, D., ... & Zilberman, N. (2019). Measuring global ocean heat content to estimate the Earth energy imbalance. Frontiers in Marine Science, 6, 432. https://doi.org/10.3389/fmars.2019.00432

Miguez, B. M., Testut, L., & Wöppelmann, G. (2008). The Van de Casteele test revisited: an efficient approach to tide gauge error characterization. *Journal of Atmospheric and Oceanic Technology*, 25(7), 1238-1244. https://doi.org/10.1175/2007JTECHO554.1

Mitchell Jr, J. M. (1961). Recent secular changes of global temperature. Annals of the New York Academy of Sciences, 95(1), 235-250.

Mitrovica, J. X., Hay, C., Kopp, R., & Lickley, M. (2018). All sea level is local. Bulletin of the Atomic Scientists, 74(3), 142-147.https://doi.org/10.1080/00963402.2018.1461935

Möller, F. (1963). On the influence of changes in the CO2 concentration in air on the radiation balance of the earth's surface and on the climate. Journal of Geophysical Research, 68(13), 3877-3886. https://doi.org/10.1029/JZ068i013p03877

Montgomery, R. B. (1937). Fluctuations in monthly sea level on eastern US coast as related to dynamics of western North Atlantic Ocean. J. mar. Res., 8, 165-185.

Moore, J., Grinsted, A., & Jevrejeva, S. (2006). Is there evidence for sunspot forcing of climate at multi-year and decadal periods?. Geophysical research letters, 33(17).

Moray, R. (1667) Considerations and enquiries concerning tides, by Sir Robert Moray; likewise for a further search into Dr. Wallis's newly publish't hypothesis. Philosophical Transactions. Vol 1, 17. Pp 298-301. https://doi.org/10.1098/rstl.1665.0113

Morice, C. P., Kennedy, J. J., Rayner, N. A., Winn, J. P., Hogan, E., Killick, R. E., ... & Simpson, I. R. (2020). An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. Journal of Geophysical Research: Atmospheres, e2019JD032361. https://doi.org/10.1029/2019JD032361

Mudge, W., & Colby, T. (1811). An Account of the Trigonometrical Survey, Carried on by Order of the Master-General of His Majesty's Ordnance, in the Years 1800-1809 (Vol. 3). Faden, London.

Natarov, S. I., Merrifield, M. A., Becker, J. M., & Thompson, P. R. (2017). Regional influences on reconstructed global mean sea level. Geophysical Research Letters, 44(7), 3274-3282. https://doi.org/10.1002/2016GL071523

Nauels, A., Gütschow, J., Mengel, M., Meinshausen, M., Clark, P. U., & Schleussner, C. F. (2019). Attributing long-term sea-level rise to Paris Agreement emission pledges. Proceedings of the National Academy of Sciences, 116(47), 23487-23492.

Neely, G. J. H. (1930) The Ordnance Survey of the Isle of Man. Proc IoM N.H.& A. Soc III #4 pp388-404 1930

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences*, 115(9), 2022-2025.

Newton, I. (1846) The mathematical principles of natural philosophy (English translation by A. Motte Published 1729). 1846 publication, Daniel Adee, New York. (Original work published 1687).

Nomitsu, T., & Okamoto, M. (1927). The causes of the annual variation of the mean sea level along the Japanese coast. Memoirs of the College of Science, Kyoto Imperial University. Series A, 10(3), 125-161.

Nowicki, S., Goelzer, H., Seroussi, H., Payne, A. J., Lipscomb, W. H., Abe-Ouchi, A., ... & Wal, R. V. D. (2020). Experimental protocol for sea level projections from ISMIP6 stand-alone ice sheet models. The Cryosphere, 14(7), 2331-2368.

Ogura, S. (1925). Effect of atmospheric pressure on sea-level in the western part of the North Pacific Ocean. Japanese Journal of Astronomy and Geophysics, 2, 209-231.

Oldham, J., Bateman, J. F., Scott Russell, J., Thompson, T. (1863) Report on Tidal Observations on the Humber. *Report of the Thirty Second Meeting of the British Association for the Advancement of Science*, Cambridge, September 1862. Pp 101-103. John Murray, London.

Oldham, J., Bateman, J. F., Scott Russell, J., Thompson, T. (1865) Report on Tidal Observations made on the Humber and Rivers Trent and Ouse. *Report of the Thirty Fourth Meeting of the British Association for the Advancement of Science*, Bath, September 1864. Pp 129-188. John Murray, London.

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Ortt, F. L. (1897). The effect of wind and atmospheric pressure on the tides. Nature, 56(1439), 80-84.

OS (1899) Spirit Levelling in England and Wales. Abstracts of tidal observations.

Palmer, H.R. (1831). Description of graphical register of tides and winds. Phil. Trans. R. Soc. Lond., 121, 209-213, doi:10.1098/rstl.1831.0013.

Palmer, M. D., Gregory, J. M., Bagge, M., Calvert, D., Hagedoorn, J. M., Howard, T., ... & Spada, G. (2020). Exploring the drivers of global and local sea-level change over the 21st century and beyond. Earth's Future, 8(9), e2019EF001413.

Palmer, M. D., Domingues, C. M., Slangen, A. B., & Dias, F. B. (2021). An ensemble approach to quantify global mean sea-level rise over the 20th century from tide gauge reconstructions. Environmental Research Letters.

Papadopoulos, A., & Tsimplis, M. N. (2006). Coherent coastal sea-level variability at interdecadal and interannual scales from tide gauges. Journal of Coastal Research, 22(3 (223)), 625-639.

Parks, M.T. (1857). Results of an examination of the records of the Liverpool Self-registering tide gauge, for the years 1854, 1855 and 1856. Transactions of the Lancashire and Cheshire Historic Society, 9, 223-226.

Parry, W. E. (1821) Journal of a Voyage for the Discovery of a North-West Passage from the Atlantic to the Pacific: Performed in the Years 1819-20 in His Majesty's Ships Hecla and Griper, Volume 1. Murray, London.

Parry, W. E., & Hooker, W. J. (1825). Appendix to Captain Parry's Journal of a Second Voyage for the Discovery of a North-west Passage from the Atlantic to the Pacific: Performed in Majesty's Ships Fury and Hecla, in the Years 1821-22-23. J. Murray.

Payne, A. J., Nowicki, S., Abe-Ouchi, A., Agosta, C., Alexander, P., Albrecht, T., ... & Zwinger, T. (2021). Future sea level change under CMIP5 and CMIP6 scenarios from the Greenland and Antarctic ice sheets. Geophysical Research Letters, e2020GL091741. https://doi.org/10.1029/2020GL091741

Peltier, W. R., & Tushingham, A. M. (1989). Global sea level rise and the greenhouse effect: might they be connected?. Science, 244(4906), 806-810.

Peltier, W.R., Tushingham, A.M., (1991). Influence of glacial isostatic adjustment on tide gauge measurements of secular sea level change. J. Geophys. Res. 96, 6779–6796.

Peltier, W.R., Argus, D.F. and Drummond, R. (2015) Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G_C (VM5a) model. *J. Geophys. Res. Solid Earth*, 120, 450-487, doi:10.1002/2014JB011176.

Penna, N. T., Featherstone, W. E., Gazeaux, J., & Bingham, R. J. (2013). The apparent British sea slope is caused by systematic errors in the levelling-based vertical datum. Geophysical Journal International, 194(2), 772-786. Doi: 10.1093/gji/ggt161

Piecuch, C. G., P. R. Thompson, and K. A. Donohue (2016), Air pressure effects on sea level changes during the twentieth century, J. Geophys. Res. Oceans, 121, 7917–7930, doi:10.1002/2016JC012131.

Pirazzoli, P. A. (1986). Secular trends of relative sea-level (RSL) changes indicated by tide-gauge records. Journal of Coastal Research, 1-26.

Pfeffer, J., & Allemand, P. (2016). The key role of vertical land motions in coastal sea level variations: A global synthesis of multisatellite altimetry, tide gauge data and GPS measurements. *Earth and Planetary Science Letters*, 439, 39-47. https://doi.org/10.1016/j.epsl.2016.01.027

Philips, J. (1869) Vesuvius. Pg. 246. Clarendon Press, Oxford.

Picard, J., de La Hire, P. (1680) Observations faites a Brest et a Nantes pendant l'année 1679. Voyage d'Uranibourg ou Observations Astronomiques faites en Danemarck par M. Picard. Pp 49-56. Imprimerie Royale, France.

Piecuch, C.G., Calafat, F.M., Dangendorf, S. Jordà, G. (2019). The Ability of Barotropic Models to Simulate Historical Mean Sea Level Changes from Coastal Tide Gauge Data. Surv Geophys. https://doi.org/10.1007/s10712-019-09537-9

Playfair, J. (1798). XII. Meteorological Abstract for the Years 1794, 1795, and 1796. Transactions of the Royal Society of Edinburgh, 4(2), 213-222. doi:10.1017/S0080456800030854

Poli, P., H. Hersbach, D.P. Dee, P. Berrisford, A.J. Simmons, F. Vitart, P. Laloyaux, D.G. Tan, C. Peubey, J. Thépaut, Y. Trémolet, E.V. Hólm, M. Bonavita, L. Isaksen, and M. Fisher. ERA-20C: An Atmospheric Reanalysis of the Twentieth Century, Journal of Climate, 2016, 29:11, 4083-4097, Doi: 10.1175/JCLI-D-15-0556.1

Ponte, R. M. (2006). Low-frequency sea level variability and the inverted barometer effect. *Journal of Atmospheric and Oceanic Technology*, 23(4), 619-629.

Press, W. H., & Rybicki, G. B. (1989). Fast algorithm for spectral analysis of unevenly sampled data. The astrophysical journal, 338, 277-280.

Pugh D.T. and Woodworth P.L. (2014). Sea Level Science, Cambridge University Press.

Pugh, D. T. (1972). The physics of pneumatic tide gauges. *The International Hydrographic Review*, 49(2).

Pugh, D. T. (1981). Comparative tests of sea level data from the Newlyn tide well and an Aanderaa pneumatic system.

Pugh, D., & Woodworth, P. (2014). Sea-level science: understanding tides, surges, tsunamis and mean sea-level changes. Cambridge University Press.

Pugh, D., Hunter, J., Coleman, R., & Watson, C. (2002). A comparison of historical and recent sea level measurements at Port Arthur, Tasmania. International Hydrographic Review, 3(3), 27-46.

Pugh, D. T., Bridge, E., Edwards, R., Hogarth, P., Westbrook, G., Woodworth, P. L., and McCarthy, G. D.: Mean Sea Level and Tidal Change in Ireland since 1842: A case study of Cork, Ocean Sci. Discuss. [preprint], https://doi.org/10.5194/os-2021-49, in review, 2021.

Pugh, D.T. (1982) A comparison of recent and historical tides and mean sea-levels off Ireland. Geophysical Journal of the Royal Astronomical Society, 71, 809-815.

Rahmstorf, S., & Vermeer, M. (2011). Discussion of: Houston, JR and Dean, RG, 2011. Sea-Level Acceleration Based on US Tide Gauges and Extensions of Previous Global-Gauge Analyses. Journal of Coastal Research, 27 (3), 409-417. Journal of Coastal Research, 27(4), 784-787.

Raible, C. C., Brönnimann, S., Auchmann, R., Brohan, P., Frölicher, T. L., Graf, H. F., ... & Wegmann, M. (2016). Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects. Wiley Interdisciplinary Reviews: Climate Change, 7(4), 569-589. https://doi.org/10.1002/wcc.407

Rappleye, H. S. (1938). The sea-level datum of 1929. Eos, Transactions American Geophysical Union, 19(1), 51-55.

Ravenstein, E. G. (1886). On Bathy-Hypsographical Maps; With Special Reference to a Combination of the Ordnance and Admiralty Surveys. In Proceedings of the Royal Geographical Society and Monthly Record of Geography (Vol. 8, No. 1, pp. 21-27). Royal Geographical Society (with the Institute of British Geographers), Wiley.

Redman, J. B. (1877a). The River Thames.(Includes Plates and Appendix). Minutes of the Proceedings of the Institution of Civil Engineers, Vol. 49, January, pp. 67-114. Thomas Telford.

Redman, J. B. (1883). The River Thames.(Including Appendix). Minutes of the Proceedings of the Institution of Civil Engineers, Vol. 72, January, pp. 254-261. Thomas Telford.

Redman, J., Coope, O., Shoolbred, J., Airy, S. G., Abernethy, J., Unwin, W., ... & Russell, J. (1877b). Discussion. The River Thames. (Includes Plate). Minutes of the Proceedings of the Institution of Civil Engineers Vol. 49, pp.115-159. Thomas Telford.

Reidy, M. S. (2009). Tides of History: Ocean Science and Her Majesty's Navy. University of Chicago Press.

Rennie A.F. and Hansom J.D (2011) Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland’s coast. Geomorphology 125, 193-202.

Rohde, R. A. and Hausfather, Z. (2020). The Berkeley Earth Land/Ocean Temperature Record, Earth Syst. Sci. Data, 12, 3469–3479, https://doi.org/10.5194/essd-12-3469-2020.

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., & Lenaerts, J. T. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. Geophysical Research Letters, 38(5).

Roberts, B. (1950). Norwegian-British-Swedish Antarctic Expedition, 1949–52. Polar Record, 5(39), 463-466. doi:10.1017/S0032247400045010

Roberts E. (1913). Re-reduction of Dover Tidal Observations, 1883-84. Proc.R.Soc.Lond, 88, 230-233.

Roberts, C. D., Calvert, D., Dunstone, N., Hermanson, L., Palmer, M. D., & Smith, D. (2016). On the drivers and predictability of seasonal-to-interannual variations in regional sea level. Journal of Climate, 29(21), 7565-7585.

Ross, J., C. (1847) A Voyage of Discovery and Research in the Southern and Antarctic Regions During the Years 1839-1843, Volume 2. J. Murray.

Ross, J. C. (1854). XII. On the effect of the pressure of the atmosphere on the mean level of the ocean. Philosophical Transactions of the Royal Society of London, (144), 285-296.

Rossi, V., Horton, B. P., Corbett, D. R., Leorri, E., Perez-Belmonte, L., & Douglas, B. C. (2011). The application of foraminifera to reconstruct the rate of 20th century sea level rise, Morbihan Golfe, Brittany, France. Quaternary Research, 75(1), 24-35.

Rossiter, J. R. (1954). The North Sea storm surge of 31 january and 1 february 1953. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 246(915), 371-400.

Rossiter, J. R. (1967). An analysis of annual sea level variations in European waters. *Geophysical Journal International*, 12(3), 259-299.

Rossiter, J. R., (1972). Sea-level observations and their secular variation. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 272(1221), 131-139.

Royston, S., Watson, C. S., Legrésy, B., King, M. A., Church, J. A., & Bos, M. S. (2018). Sea-level trend uncertainty with Pacific climatic variability and temporally-correlated noise. Journal of Geophysical Research: Oceans, 123(3), 1978-1993.

Rude, G. T. (1926). Determination of mean sea-level at secondary stations. *American Journal of Science*, (64), 312-314.

Russell, H. C. (1885) Anniversary Address, J. & Proc. Roy. Soc. New South Wales, 19, 1-27

Sabine, E. (1823). Experiments to Ascertain the Length of the Seconds Pendulum, at Columbia College, New York.

Sabine, E. (1824). XVI. A comparison of barometrical measurement, with the trigonometrical determination of a height at Spitzbergen. Philosophical Transactions of the Royal Society of London, (114), 290-309.

Santamaría-Gómez, A., Gravelle, M., Dangendorf, S., Marcos, M., Spada, G., & Wöppelmann, G. (2017). Uncertainty of the 20th century sea-level rise due to vertical land motion errors. *Earth and Planetary Science Letters*, 473, 24-32.

Sasgen, I., Wouters, B., Gardner, A. S., King, M. D., Tedesco, M., Landerer, F. W., ... & Fettweis, X. (2020). Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. Communications Earth & Environment, 1(1), 1-8. https://doi.org/10.1038/s43247-020-0010-1

Scargle, J. D. (1982). Studies in astronomical time series analysis. II-Statistical aspects of spectral analysis of unevenly spaced data. The Astrophysical Journal, 263, 835-853.

Schoolbred, J. N. (1876a) On the Changes in the Tidal Portion of the River Mersey, and in its Estuary. (Includes Plates and Appendix). Minutes of the Proceedings of the Institution of Civil Engineers. Vol. 46: pp 20-49

Schoolbred, J. N. (1876b) Tides in the River Mersey. Half Tide Level at Liverpool. Report of the Forty Fifth Meeting of the British Association for the Advancement of Science, Bristol, August 1875, pp 161-164. Taylor and Francis.

Schoolbred, J. N. (1906) The tidal Regime of the River Mersey as affected by Recent Dredgings at the Bar in Liverpool Bay. Proc. R. Soc. Lond. A Vol. 78, September, pp 161-166; DOI: 10.1098/rspa.1906.0068.

Schoolbred, J. N., (1878) On tides in the Irish Sea and in the River Mersey, Proc. Lit. Phil. Soc. Liverpool, sixty-seventh session, No.XXXII, pp 359-383.

Schureman, P. (1936) Variation in yearly sea level, p. 23- 25 in: Bowie, Geodetic operations in the United States, January 1, 1933, to December 31, 1935. l. Coast and Geodetic Survey, Spec. Pub. no. 207, p. 1- 25, 1936.

Schwalm, C. R., Glendon, S., & Duffy, P. B. (2020). RCP8. 5 tracks cumulative CO2 emissions. Proceedings of the National Academy of Sciences, 117(33), 19656-19657.

Seibt, W. (1885). Das Mittelwasser der Ostsee bei Travemünde. Stankiewicz.

Shankland, E. C. (1926). Modern harbours: conservancy and operations; a work of descriptive and technical reference. J. Brown & son.

Shankland, E. C. (1932). The hydrography & cartography of a great seaport. The International Hydrographic Review, (2).

Shaw, D. (1965). Sunspots and temperatures. Journal of Geophysical Research, 70(20), 4997-4999.

Shelford, W. (1869) On the Outfall of the River Humber. Minutes of the Proceedings of the Institution of Civil Engineers. xxviii, Pp 472-492.

Shennan I., Milne, G. and Bradley, S. (2012). Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. Journal of Quaternary Science, 27, 64-70, doi:10.1002/jqs.1532.

Shennan, I., Bradley, S. L., & Edwards, R. (2018). Relative sea-level changes and crustal movements in Britain and Ireland since the Last Glacial Maximum. Quaternary Science Reviews, 188, 143-159.

Shortt, J. (1889). Notes on the possible oscillation of levels of land and sea in Tasmania during recent years. In Papers & Proceedings of the Royal Society of Tasmania (pp. 18-20).

Siegismund, F., Köhl, A., Rummel, R., & Stammer, D. (2020). Temporal Variations of the Marine Geoid. Journal of Geophysical Research: Oceans, 125(11), e2020JC016433. https://doi.org/10.1029/2020JC016433

Simmons, A. J. and Gibson, J. K. (2000). The ERA-40 Project Plan, ERA40 Project Report Series No. 1 ECMWF. Shinfield Park, Reading, UK, 63 pp

Simon, K. M., & Riva, R. E. M. (2020). Uncertainty Estimation in Regional Models of Long-Term GIA Uplift and Sea Level Change: An Overview. Journal of Geophysical Research: Solid Earth, 125(8), e2019JB018983.

Simon, K. M., Riva, R. E., Kleinherenbrink, M., & Frederikse, T. (2018). The glacial isostatic adjustment signal at present day in northern Europe and the British Isles estimated from geodetic observations and geophysical models. Solid Earth, 9(3), 777.

Slater, T., Hogg, A.E. & Mottram, R. Ice-sheet losses track high-end sea-level rise projections. Nat. Clim. Chang. 10, 879–881 (2020). https://doi.org/10.1038/s41558-020-0893-y

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Le Blancq, F., Lee, T., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moore, G. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C., Tinz, B., Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K. and Wyszyński, P. (2019), Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. Q J R Meteorol Soc. https://doi.org/10.1002/qj.3598

Smith, R. A. (2002). Historical Golden Gate tidal series: NOAA Technical Report NOS CO-OPS 035.

Smyth, T. (1866) Minutes of 11th meeting of Edinburgh Geological Society. The Geological Magazine. Vol 3. Pg 427.

SOI (1905) General Report on the Operations of the Survey of India. Administered under the Government of India during 1903-04. Appendix, The Tidal Operations. xxxvi. Govt. Printers, Calcutta.

SOI (1928) Tidal Observatories. Geodetic Report Vol II. From 1st October 1925 to 30th September 1926. Survey of India. Dehra Dun.

Spada, G., & Galassi, G. (2012). New estimates of secular sea level rise from tide gauge data and GIA modelling. Geophysical Journal International, 191(3), 1067-1094. https://doi.org/10.1111/j.1365-246X.2012.05663.x

Spencer, N. E., Woodworth, P. L., & Pugh, D. T. (1988). Ancillary time series of mean sea level measurements. Permanent Service for Mean Sea Level.

Squire, T. (1821) Barometric observations. Philosophical Magazine and Journal. Vol. 57. Pg 156. Richard and Arthur Taylor, London.

Stenchikov, G. (2021). The role of volcanic activity in climate and global changes. In Climate change (pp. 607-643). Elsevier.

Stevenson, D. (1842) A Treatise on the Application of Marine Surveying & Hydrometry to the Practice of Civil Engineering. A. and C. Black. Edinburgh.

Strauss, B. H., Kulp, S. A., Rasmussen, D. J., & Levermann, A. (2021). Unprecedented threats to cities from multi-century sea level rise. Environmental Research Letters.

Strickland, H. E. (1812). A General View of the Agriculture of the East-Riding of Yorkshire (No. 20469). Thomas Wilson and Son, High Ousegate

Sturges W, Douglas BC (2011) Wind effects on estimates of sea level rise. J Geophys Res Ocean. https://doi.org/10.1029/2010J C006492

Sturmy, S (1668) An account of some observations, made this year by Capt. Samuel Sturmy in Hong-road within four miles of Bristol, in answer to some of the queries concerning the tydes. Pp 813 – 817. https://doi.org/10.1098/rstl.1668.0052

Suthons, C. C. (1937). The computation of mean sea level. *Bulletin Géodésique*, 55(1), 65-68.

Taherkhani, M., Vitousek, S., Barnard, P. L., Frazer, N., Anderson, T. R., & Fletcher, C. H. (2020). Sea-level rise exponentially increases coastal flood frequency. Scientific reports, 10(1), 1-17.

Talke, S. A., & Jay, D. A. (2013). Nineteenth Century North American and Pacific Tidal Data: Lost or Just Forgotten?. Journal of Coastal Research.

Talke, S. A., & Jay, D. A. (2017). Archival water-level measurements: Recovering historical data to help design for the future.

Talke, S. A., Kemp, A. C., & Woodruff, J. (2018). Relative sea level, tides, and extreme water levels in Boston Harbor from 1825 to 2018. Journal of Geophysical Research: Oceans, 123(6), 3895-3914.

Talke, S. A., Mahedy, A., Jay, D. A., Lau, P., Hilley, C., & Hudson, A. (2020). Sea level, tidal, and river flow trends in the lower Columbia River Estuary, 1853–present. Journal of Geophysical Research: Oceans, 125(3), e2019JC015656.

Talke, S. A., & Jay, D. A. (2020). Changing tides: The role of natural and anthropogenic factors. Annual Review of Marine Science, 12, 121-151. 10.1146/annurev-marine-010419-010727

Talke, S. A., Familkhalili, R., & Jay, D. A. (2021). The influence of channel deepening on tides, river discharge effects, and storm surge. Journal of Geophysical Research: Oceans, e2020JC016328.

Tamisiea, M. E. (2011). Ongoing glacial isostatic contributions to observations of sea level change. Geophysical Journal International, 186(3), 1036-1044. https://doi.org/10.1111/j.1365-246X.2011.05116.x

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., ... & Velicogna, I. (2019). Contributions of GRACE to understanding climate change. Nature climate change, 9(5), 358-369. https://doi.org/10.1038/s41558-019-0456-2

Teferle, F. N., Bingley, R. M., Dodson, A. H., Penna, N. T., & Baker, T. F. (2002). Using GPS to separate crustal movements and sea level changes at tide gauges in the UK. In Vertical reference systems (pp. 264-269). Springer, Berlin, Heidelberg.

Thompson, D'Arcy W. (1913). Variation of Mean Sea-Level. Nature, 91(2285), 607-607.

Thompson, D'Arcy W. (1914). On mean sea level and its fluctuations. Fisheries Board for Scotland. Scientific Investigations Vol. IV. Edinburgh: HMSO.

Thompson, K. R. (1981). The response of southern North Sea elevations to oceanographical and meteorological forcing. *Estuarine, Coastal and Shelf Science*, 13(3), 287-301.

Thompson, K.R. (1980). An analysis of British monthly mean sea level. Geophysical Journal of the Royal Astronomical Society, 63, 57-73. Doi:10.1111/j.1365-246X.1980.tb02610.x

Thomson, W. (1868) Committee for the purpose of promoting the extension, improvement, and harmonic analysis of Tidal Observations. Report of the Thirty-Eighth Meeting of the British Association for the Advancement of Science; Held at Norwich in August 1868. London: J. Murray, Albemarle Street, London.

Thomson, W., Adams, J. C., Oldham, J., Parkes, W., Rankine, W. J. M., Richards, G. H. (1873). Report of the Committee appointed fur the purpose of promoting the extension, improvement, and harmonic analysis of Tidal Observations. Report of the Forty Second Meeting of the British Association for the Advancement of Science, Brighton, August 1872. Pp 355-394. British Association for the Advancement of Science, J. Murray. London.

Thomson, W., Major-General Strachey, Galton, D., Deacon, G. F., Field, R., Roberts, E., Schoolbred, J. N. (1879). Third Report of the Committee appointed for the purpose of considering the Datum-level of the Ordnance Survey of Great Britain, with a view to its establishment on a surer foundation than hitherto, and for the tabulation and comparison of other Datum-marks. Report of the Forty Ninth Meeting of the British Association for the Advancement of Science, Sheffield, August 1879. Pp 219-223. British Association for the Advancement of Science, J. Murray. London.

Thorarinsson, S. (1940). Present glacier shrinkage, and eustatic changes of sea-level. Geografiska Annaler, 22(3-4), 131-159.

Tinker, J., Palmer, M. D., Copsey, D., Howard, T., Lowe, J. A., & Hermans, T. H. (2020). Dynamical downscaling of unforced interannual sea-level variability in the North-West European shelf seas. Climate Dynamics, 55(7), 2207-2236. https://doi.org/10.1007/s00382-020-05378-0

Tokarska, K. B., Hegerl, G. C., Schurer, A. P., Ribes, A., & Fasullo, J. T. (2019). Quantifying human contributions to past and future ocean warming and thermosteric sea level rise. Environmental Research Letters, 14(7), 074020. https://doi.org/10.1088/1748-9326/ab23c1

Toohey, M., Krüger, K., Schmidt, H., Timmreck, C., Sigl, M., Stoffel, M., & Wilson, R. (2019). Disproportionately strong climate forcing from extratropical explosive volcanic eruptions. Nature Geoscience, 12(2), 100-107. https://doi.org/10.1038/s41561-018-0286-2

Trauth, M.H., Sillmann, E. (2018) Collecting, Processing and Presenting Geoscientific Information, MATLAB and Design Recipes for Earth Sciences – Second Edition. Springer Verlag, 274 p., Supplementary Electronic Material, Hardcover, ISBN: 978-3-662-56202-4. (MDRES)

Trenberth, K. E. (2020). Understanding climate change through Earth's energy flows. Journal of the Royal Society of New Zealand, 50(2), 331-347.https://doi.org/10.1080/03036758.2020.1741404

Tsimplis, M. N., & Woodworth, P. L. (1994). The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data. Journal of Geophysical Research: Oceans, 99(C8), 16031-16039.

Tushingham, A., & Peltier, W. R. (1991). Ice-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. Journal of Geophysical Research: Solid Earth, 96(B3), 4497-4523.

Tylor, A. (1869). On the Formation of Deltas, and on the Evidence and Cause of great Changes in the Sea-Level during the Glacial Period. Quarterly Journal of the Geological Society, 25(1-2), 7-12. https://doi.org/10.1144/GSL.JGS.1869.025.01-02.10

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M., et al. (2005). The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, 131(612), 2961–3012. https://doi.org/10.1256/qj.04.176

Valentin, H. (1953). Present vertical movements of the British Isles. The Geographical Journal, 119(3), 299-305.

Van Veen, J. (1945). Bestaat er een geologische bodemdaling te Amsterdam sedert 1700. Tijdschr K Ned Aardr Gen, 62, 2-36. Amsterdam.

Van Veen, J. (1954). Tide-gauges, subsidence-gauges and flood-stones in the Netherlands. Geologie en Mijnbouw, 16(6), 214-219.

Veng, T., & Andersen, O. B. (2020). Consolidating sea level acceleration estimates from satellite altimetry. Advances in Space Research.

Vishwakarma, B. D., Royston, S., Riva, R. E. M., Westaway, R. M., & Bamber, J. L. (2020). Sea level budgets should account for ocean bottom deformation. Geophysical research letters, 47(3), e2019GL086492.

Visser, H., Dangendorf, S., & Petersen, A. C. (2015). A review of trend models applied to sea level data with reference to the “acceleration-deceleration debate”. Journal of Geophysical Research: Oceans, 120(6), 3873-3895. https://doi.org/10.1002/2015JC010716

Volkov, D. L., Baringer, M., Smeed, D., Johns, W., & Landerer, F. W. (2019). Teleconnection between the Atlantic Meridional Overturning Circulation and sea level in the Mediterranean Sea. *Journal of Climate,* 32(3), 935-955.

Waalewijn, A. (1987). The Amsterdam ordnance datum (NAP). Survey Review, 29(226), 197-204.

Wahl, T., Haigh, I.D., Woodworth, P.L., Albrecht, F., Dillingh, D., Jensen, J., Nicholls, R.J., Weisse, R. and Wöppelmann, G. (2013). Observed mean sea level changes around the North Sea coastline from 1800 to present. Earth-Science Reviews, 124, 51-67.

Wakelin, S. L., Woodworth, P. L., Flather, R. A., & Williams, J. A. (2003). Sea-level dependence on the NAO over the NW European Continental Shelf. *Geophysical Research Letters*, 30(7).

Walden, A. T. (1982) The statistical analysis of extreme high sea levels utilising data from the Solent. PhD Thesis, Southampton University.

Walker, J. (1835) Port of Edinburgh: Report on its improvement. Pp 1-16. Ibotson and Palmer, London.

Walker, W. (1846) Observations on the Tides deduced from tidal observations made in Plymouth Dockyard from August 1831 to September 1833. Condensed from a lecture delivered at the Plymouth Institution. By William Walker Esq. Assistant Master Attendant. The Mechanic's Magazine, Museum, Register, Journal and Gazette, Volume 45, pp 246-251 & 267-273 Robertson and Co. London.

Wallis, T. W. (1899). Autobiography of Thomas Wilkinson Wallis : sculptor in wood, and extracts from his sixty years' journal. Goulding, Louth. (Pg 203) (tide measurements at Sutton on Sea, 1881)

Wang, J., Church, J. A., Zhang, X., & Chen, X. (2021). Reconciling global mean and regional sea level change in projections and observations. Nature communications, 12(1), 1-12. https://doi.org/10.1038/s41467-021-21265-6

Watson, P. J. (2011). Is there evidence yet of acceleration in mean sea level rise around mainland Australia?. Journal of Coastal Research, 27(2), 368-377. https://doi.org/10.2112/JCOASTRES-D-10-00141.1

Webber, N.B., Walden, A.T. (1981). Rise in mean sea level at Portsmouth. Dock and Harbour Authority, 61, p. 385.

Webster, T. (1848). The Port and Docks of Birkenhead with maps, plans, sections and tidal diagrams, and an account of the Acts of Parliament relating to the Mersey and Dock Estate of Liverpool. Table of Levels. Chapman and Hall, London.

Wenzel, M., & Schröter, J. (2010). Reconstruction of regional mean sea level anomalies from tide gauges using neural networks. Journal of Geophysical Research: Oceans, 115(C8).

Whewell, W. (1835). V. On the results of tide observations made in June 1834 at the coast guard stations in Great Britain and Ireland. Philosophical Transactions of the Royal Society of London, (125), 83-90.

Whewell, W. (1836a). Researches on the Tides. Fourth Series. On the Empirical Laws of the Tides in the Port of Liverpool. Philosophical Transactions of the Royal Society of London, 1-15.

Whewell, W. (1836b). Researches on the tides; sixth series. On the results of an extensive system of tide observations, made on the coasts of Europe and America, in June 1835. Philosophical Transactions of the Royal Society of London. 126, Part II. Pp 289-341. Richard Taylor, London.

Whewell, W. (1837). Researches on the Tides. Seventh Series. On the Diurnal Inequality of the Height of the Tide, Especially at Plymouth and at Singapore; And on the Mean Level of the Sea. Philosophical Transactions of the Royal Society of London, 75-85.

Whewell, W. (1838a). Researches on the Tides. Ninth Series. On the Deduction of the Laws of the Tides, from Short Series of Observations.[Abstract]. In Abstracts of the Papers Printed in the Philosophical Transactions of the Royal Society of London January. (pp. 72-73). The Royal Society.

Whewell, W. (1838b). Description of a new tide-gauge, constructed by Mr. T.G. Bunt, and erected on the eastern bank of the River Avon, in front of the Hotwell House, Bristol, 1837. Phil. Trans. R. Soc. London, 128, 249-251, https://doi.org/10.1098/rstl.1838.0012

Whewell, W. (1839). XI. Researches on the tides. Tenth series. On the laws of low water at the port of Plymouth, and on the permanency of mean water. Philosophical Transactions of the Royal Society of London, (129), 151-161.

Whewell, W. (1840). XLVI. On the mean level of the sea. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 17(111), 321-325.

Whewell, W. (1840b). VI. Additional note to the eleventh series of researches on the tides. Philosophical Transactions of the Royal Society of London, (130), 161-174.

Whewell, W. (1842) Report on the Discussion of Leith Tide Observations, Executed by Mr. D. Ross, of the Hydrographer's Office, Admiralty, under the Direction of the Rev. W. Whewell. British Association for the Advancement of Science. Meeting. (Vol. 11). Pp33-36. J. Murray. London.

Whitehouse, P. L. (2018). Glacial isostatic adjustment modelling: historical perspectives, recent advances, and future directions. *Earth surface dynamics*., 6(2), 401-429.

Willett, H. C. (1950). Temperature Trends of the Past Century. Royal Meteorological Society Centenary Proceedings pp. 195-206. London: Royal Meteorological Society.

Wilkins, E. M. (1961). Seasonal variations in atmospheric carbon dioxide concentration. *Journal of Geophysical Research*, 66(4), 1314-1315. https://doi.org/10.1029/JZ066i004p01314

Williams, S. D. (2003). Offsets in global positioning system time series. *Journal of Geophysical Research: Solid Earth*, 108(B6).

Williams, S. D. (2008). CATS: GPS coordinate time series analysis software. GPS solutions, 12(2), 147-153.

Williams, S. D., Moore, P., King, M. A., & Whitehouse, P. L. (2014). Revisiting GRACE Antarctic ice mass trends and accelerations considering autocorrelation. *Earth and Planetary Science Letters*, 385, 12-21. https://doi.org/10.1016/j.epsl.2013.10.016

Wong, E. W., & Minnett, P. J. (2018). The response of the ocean thermal skin layer to variations in incident infrared radiation. *Journal of Geophysical Research: Oceans*, 123(4), 2475-2493.

Woodworth, P. L. (1987). Trends in UK mean sea level. *Marine Geodesy*, 11(1), 57-87.

Woodworth, P. L. (1990). A search for accelerations in records of European mean sea level. International Journal of Climatology, 10(2), 129-143.

Woodworth, P. L. (1991). The permanent service for mean sea level and the global sea level observing system. *Journal of Coastal Research*, 699-710.

Woodworth, P. L., Vassie, J. M., Spencer, R., & Smith, D. E. (1996). Precise datum control for pressure tide gauges. *Marine Geodesy*, 19(1), 1-20. https://doi.org/10.1080/01490419609388068

Woodworth, P. L. (1999). High waters at Liverpool since 1768: the UK's longest sea level record. Geophysical Research Letters, 26(11), 1589-1592.

Woodworth, P. L., Tsimplis, M. N., Flather, R. A., & Shennan, I. (1999). A review of the trends observed in British Isles mean sea level data measured by tide gauges. Geophysical Journal International, 136(3), 651-670.

Woodworth, P. L., & Smith, D. E. (2003). A one year comparison of radar and bubbler tide gauges at Liverpool. *The International hydrographic review*, 4(3).

Woodworth, P. L., Teferle, F. N., Bingley, R. M., Shennan, I., & Williams, S. D. P. (2009a). Trends in UK mean sea level revisited. *Geophysical Journal International*, 176(1), 19-30.

Woodworth, P. L., White, N. J., Jevrejeva, S., Holgate, S. J., Church, J. A., & Gehrels, W. R. (2009b). Evidence for the accelerations of sea level on multi-decade and century timescales. International Journal of Climatology: A Journal of the Royal Meteorological Society, 29(6), 777-789.

Woodworth, P. L., Pugh, D. T., & Bingley, R. M. (2010). Long-term and recent changes in sea level in the Falkland Islands. Journal of Geophysical Research: Oceans, 115(C9).

Woodworth, P. L., Gehrels, W. R., & Nerem, R. S. (2011). Nineteenth and twentieth century changes in sea level. Oceanography, 24(2), 80-93.

Woodworth, P. L. (2012). A note on the nodal tide in sea level records. Journal of Coastal Research, 28(2), 316-323.

Woodworth, P. L. (2017). Differences between mean tide level and mean sea level. *Journal of Geodesy*, 91(1), 69-90. https://doi.org/10.1007/s00190-016-0938-1

Woodworth, P. L. (2018). Sea level change in Great Britain between 1859 and the present. Geophysical Journal International, 213(1), 222-236.

Woodworth, P. L., & Rowe, G. H. (2018). The tidal measurements of James Cook during the voyage of the Endeavour. History of Geo-and Space Sciences, 9(1), 85-103.

Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., ... & Merrifield, M. A. (2019). Forcing factors affecting sea level changes at the coast. Surveys in Geophysics, 40(6), 1351-1397.

Woodworth, P. L., Hunter, J. R., Marcos, M., & Hughes, C. W. (2021). Towards reliable global allowances for sea level rise. Global and Planetary Change, 103522.

Wöppelmann, G., Pouvreau, N., Coulomb, A., Simon, B., & Woodworth, P. L. (2008). Tide gauge datum continuity at Brest since 1711: France's longest sea-level record. Geophysical Research Letters, 35(22).

Wöppelmann, G., Marcos, M., Coulomb, A., Míguez, B.M., Bonnetain, P., Boucher, C., Gravelle, M., Simon, B. and Tiphaneau, P., (2014). Rescue of the historical sea level record of Marseille (France) from 1885 to 1988 and its extension back to 1849–1851. Journal of Geodesy, 88(9), pp.869-885.

Wöppelmann, G., & Marcos, M. (2016). Vertical land motion as a key to understanding sea level change and variability. Reviews of Geophysics, 54(1), 64-92. DOI: 10.1002/2015RG000502

Xu, Z., Ji, F., Liu, B., Feng, T., Gao, Y., He, Y., & Chang, F. (2021). Long-term evolution of global sea surface temperature trend. International Journal of Climatology. https://doi.org/10.1002/joc.7082

Zanna, L., Khatiwala, S., Gregory, J. M., Ison, J., & Heimbach, P. (2019). Global reconstruction of historical ocean heat storage and transport. Proceedings of the National Academy of Sciences, 116(4), 1126-1131. https://doi.org/10.1073/pnas.1808838115

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., ... & Cogley, J. G. (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature, 568(7752), 382-386. https://doi.org/10.1038/s41586-019-1071-0

Zervas, C. E. (2009). Sea level variations of the United States, 1854-2006.

Other sources of useful data

Ocean Volume data: Eakins, B.W. and G.F. Sharman, Volumes of the World's Oceans from ETOPO1, NOAA National Geophysical Data Center, Boulder, CO, 2010.

Harbours, Docks and Piers Clauses Act 1847
https://www.legislation.gov.uk/ukpga/Vict/10-11/27/contents/data.htm?wrap=true

Appendices

The appendix consists of the original supplementary material to the published papers (Chapters 3 and 4).

For **Chapter 4**, the supplements 4.1, 4.2 and 4.3 are available freely on-line at https://www.sciencedirect.com/science/article/pii/S0079661120300720#m0015

Supplement 4.1: supplementary data 1

Supplement 4.2: supplementary data 2

Supplement 4.3: supplementary data 3

For **Chapter 4**, there are eight supplements, which are feely available on-line at:

https://www.sciencedirect.com/science/article/pii/S0079661121000112

Supplement 5.1: supplementary data 1 *main table 4 (Excel spreadsheet)*

Supplement 5.2: supplementary data 2 *main table 4 (csv format)*

Supplement 5.3: supplementary data 3 *main table 4 (pdf)*

Supplement 5.4: supplementary data 4 *Admiralty Naval Base site bench marks*

Supplement S5.5: supplementary data 5 *Plots of MSL at each cluster site*

Supplement 5.6: supplementary data 6 *GB MSL index plus uncertainties (csv)*

Supplement 5.7: supplementary data 7 *Annual MSL data for each site (csv)*

Supplement 5.8: supplementary data 8 *supplementary tables and figures (Word)*

Supplementary table S5.4

The main table in on-line supplements 5.1,4.2 and 5.3 above is presented here as table S5.4. This summarises the useable data sources, adjustments and uncertainties for Chapter 4 of this thesis. The blue text is used to indicate observations from the OS FGL campaign of 1859/1860, described in section 5.3.3. The data is arranged in rows, grouped by main cluster name indexed alphabetically, and by sea level measurement site location. Column 1 and 2 for each site gives the year of observation, and the number of months over which observations were made. Column 3 gives the original average MTL or MSL value relative to the local tide gauge or Chart Datum (CD) used, in the original units of feet (or mm for modern measurements, 1 ft = 304.8 mm is used here). Column 4 gives the TGZ to the same datum in the original units, and column 5 and 6 gives either MTL or MSL (whichever is given) relative to local Ordnance Datum (OD), converted to mm. Column 7 gives an estimated elevation offset between MTL and MSL (mm). Column 8 gives the local bench mark derived datum elevation offset from original OD to the latest ODN revision (3rd). Column 9 gives measured MSL relative to this revised local ODN (mm). Column 10 gives an estimated average seasonal adjustment for observations of less than a year (mm), column 11 gives an estimate of the average modelled meteorological sea level adjustment required (mm) over the period of observation. Column 12, in red, gives the MSL value relative to ODN for that site over the same time period, adjusted for MTL to MSL, seasonal and meteorological factors. Column 13 and 14 give the Latitude and Longitude of the site (decimal degrees N, and E from Greenwich, respectively). Column 15 gives the PSMSL site ID number of the cluster reference PSMSL time series used as the basis for ODN offset adjustments for that site (NB, for some clusters more than one PSMSL site is used, as discussed in the text). Column 16 is the linear distance (km) between the PSMSL reference site and the observation site. Column 17 is the approximate year that the ODN fundamental bench mark levelling, as used for ODN(3), was carried out (this is the pivot year for GIA related MSL trend adjustments). Column 18 gives the modelled GIA trend, adjusted for the geoid, and column 19 gives the vertical offset due to GIA relative to levelled ODN in the pivot year (estimated from the vertical land motion over the difference in years between MSL observation and ODN levelling). Column 20 gives the levelling uncertainty (assumed related to distance between PSMSL reference site and observation site). Column 21 gives an estimate of the MTL to MSL conversion uncertainty, and column 22 gives the estimated uncertainty due to seasonal adjustment. Column 23 gives the combined uncertainty (the previous three uncertainties added in quadrature). Column 24 gives an initial estimate of the cluster site SLR. Column 25 gives the overall least squares estimated offset between each site and the mean ODN relative value (effectively, the mean vertical difference between site sea level curves and the common mode GB sea level curve, due to all contributing factors). Column 26 is simply a row index. Column 27 and 28 give either the original start and end dates of observation, or the centre date and duration of observations, to daily resolution (both formats were used by the Admiralty), where given. Column 29 gives a brief reference for the source of data, the Tidal Ledger is from the Admiralty archives, IHB is the International Hydrographic Bureau sheets, Tidal Analysis is the PSMSL tidal analysis (original calculation sheet document sometimes used by IHB and the Admiralty in late 20th Century). Column 30 gives a weighting value of zero for the small number of data points identified as outliers.

Supplementary Table S5.4

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																															
																		ODN ref				MTL to		Quad.								
									ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
					TGZ	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
Cluster	New data			MTL or	or CD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
core	location			MSL	to OD	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
station		Year	Months	ft or mm	ft or mm																											
A	St. Marys	1860	12	9.83	9.84	-3		-23		-26	4	-8	-30	49.918	-6.317	1855	0.000	1916	-0.432	24	9	12	25	29	1.687	-18	1	30-Jun-1860	354	Tidal Ledger page 383		HO
ST. MARYS	St. Marys	1887	12			0		-23		-23	0	0	-23	49.918	-6.317	1855	0.000	1916	-0.432	13	9	12	25	29		-18	2			MSL datum		
	St. Marys	1968	13	20.37	20.00		112			112	5	8	124	49.918	-6.317	1855	0.000	1916	-0.432	-22	9	0	25	26		-18	3	13-Feb-1968	384	Tidal analysis 204		
	St. Marys	1972	1	3010	2810		200			200	44	10	254	49.918	-6.317	1855	0.000	1916	-0.432	-24	9	0	26	27		-18	4	17-Apr-1972	30	Tidal analysis 205		
																											5					
B	St. Ives	1972	0.5	1870	1700		170			170	46	3	219	50.213	-5.480	202	13.045	1916	-0.367	-21	31	0	37	48	1.504	-104	6	03-May-1972	17	IHB 1336		
NEWLYN	Penzance	1849		9.72	9.50	67		16	-125	-42	0	0	-42	50.121	-5.531	202	2.127	1916	-0.376	25	12	12	37	41		-104	7	1849		Tidal Ledger page 331		
	Penzance	1859	0.5	9.57	9.57		1	0	-125	-124	35	45	-43	50.121	-5.531	202	2.127	1916	-0.376	21	12	0	34	36		-104	8	29-Jun-1859	22-Jul-1859	OS 1859		OS
	Penzance	1896	0.5				202	0	-125	77	0	0	77	50.121	-5.531	202	2.127	1916	-0.376	8	12	0	52	54		-104	9			OS 1896		OS
	Lizard Point	1961	1	10.01	9.50		155			155	35	17	207	49.959	-5.207	202	28.852	1916	-0.359	-16	46	0	24	52		-104	10	15-Jul-1961	30	IHB1051		
	Coverack	1854		10.41	10.40	3		16	-125	-106	0	0	-106	50.023	-5.094	202	33.263	1916	-0.347	22	49	12	37	63		-104	11	1854		Tidal Ledger page 57 & 58		
	Coverack	1961	1	10.01	9.65		110			110	35	17	161	50.023	-5.094	202	33.263	1916	-0.347	-16	49	0	24	55		-104	12	15-Jul-1961	30	IHB 1052		
	Falmouth	1854		9.35	9.15	61		16	-131	-54	0	0	-54	50.153	-5.066	202	34.416	1916	-0.339	21	50	12	37	63		-104	13	1854	1855	Tidal Ledger page131		
	Falmouth	1859	0.5	8.90	8.90		0	0	-131	-131	35	44	-52	50.153	-5.066	202	34.416	1916	-0.339	19	50	0	34	61		-104	14	27-Jun-1859	20-Jul-1859	OS 1859		OS
	Falmouth	1896	0.5				5	0	-131	-126	0	0	-126	50.153	-5.066	202	34.416	1916	-0.339	7	50	0	52	72		-104	15			OS 1896		OS
	Falmouth	1961	1	9.81	9.55		79			79	35	17	131	50.153	-5.066	202	34.416	1916	-0.339	-15	50	0	24	55		-104	16	15-Jul-1961	30	IHB 1053		
																											17					
C	Fowey	1856		8.89	8.83	18		143	-146	15	0	0	15	50.333	-4.633	982	32.030	1916	-0.296	18	48	12	56	75	1.461	-103	18	1856	1857	Tidal Ledger page 131		
DEVONPORT	Fowey	1961	1	9.50	9.00		152			152	44	13	209	50.333	-4.633	982	32.030	1916	-0.296	-13	48	0	36	60		-103	19	15-Jul-1961	30	IHB 1055		
	Looe East	1848		9.21	9.00	64		143	-232	-25	0	0	-25	50.233	-4.450	982	24.065	1916	-0.286	19	42	12	56	71		-103	20	1848	1849	Tidal Ledger page 246		
	Devonport	1832	7	10.22	10.67	-136		143	-137	-130	-18	14	-134	50.368	-4.185	982	0.000	1916	-0.258	22	9	12	30	33		-103	21	01-Jun-1832	31-Dec-1832	Admiralty Survey Royal Society (1833)		
	Devonport	1833	12	10.22	10.67	-135		143	-137	-129	0	-8	-137	50.368	-4.185	982	0.000	1916	-0.258	21	9	12	29	33		-103	22	01-Jan-1833	31-Dec-1833	Admiralty Survey Royal Society (1833)		
	Devonport	1834	12	10.23	10.67	-134		143	-137	-128	0	34	-94	50.368	-4.185	982	0.000	1916	-0.258	21	9	12	29	33		-103	23	01-Jan-1834	31-Dec-1834	Admiralty Survey HMSO (1835)		
	Devonport	1835	12	10.20	10.68	-147		143	-137	-141	0	21	-121	50.368	-4.185	982	0.000	1916	-0.258	21	9	12	29	33		-103	24	01-Jan-1835	31-Dec-1835	Admiralty Survey OS (1861a)		
	Devonport	1836	12	10.33	10.68	-106		143	-137	-100	0	-1	-101	50.368	-4.185	982	0.000	1916	-0.258	21	9	12	29	33		-103	25	01-Jan-1836	31-Dec-1836	Admiralty Survey OS 1861		
	Devonport	1837	12	10.19	10.68	-150		143	-137	-144	0	6	-138	50.368	-4.185	982	0.000	1916	-0.258	20	9	12	29	33		-103	26	01-Jan-1837	31-Dec-1837	Admiralty Survey OS 1861		
	Devonport	1838	12	10.50	10.68	-56		143	-137	-50	0	-4	-54	50.368	-4.185	982	0.000	1916	-0.258	20	9	12	29	33		-103	27	01-Jan-1838	31-Dec-1838	Admiralty Survey OS 1861		
	Devonport	1882	12	8.15	8.42	-82		143	-137	-76	0	-22	-98	50.368	-4.185	982	0.000	1916	-0.258	9	9	12	29	33		-103	28	15-May-1882	15-May-1883	Tidal Ledger page 91		
	Devonport	1930	0.5	8.82	8.42	122		0	-137	-15	32	6	23	50.368	-4.185	982	0.000	1916	-0.258	-4	9	0	67	68		-103	29	27-Feb-1930	13-Mar-1930	IHB 2121		
	Devonport	1934	1	8.20	8.18	6		0	-137	-131	48	8	-75	50.368	-4.185	982	0.000	1916	-0.258	-5	9	0	53	54		-103	30	20-Jun-1934	29	IHB 2131		
	Devonport	1954	12	8.84	8.30	165		0	-137	28	0	2	30	50.368	-4.185	982	0.000	1916	-0.258	-10	9	0	29	31		-103	31	22-Apr-1954	365	IHB 869		
	Salcombe	1856		8.75	8.50	76		143	-55	164	0	0	164	50.217	-3.783	982	33.164	1916	-0.232	14	49	12	56	75		-103	32	1856	1858	Tidal Ledger page 383		
	Kingswear	1960	1	8.79	8.60		57			57	39	-47	48	50.349	-3.568	982	43.871	1916	-0.211	-9	56	0	36	67		-103	33	26-Jul-1960	30	IHB 1058		
	Dartmouth	1852		7.96	8.00	-12		143	-119	12	0	0	12	50.350	-3.583	982	42.748	1916	-0.212	14	56	12	56	80		-103	34	1852		Tidal Ledger page 90		
	Dartmouth	1937		8.47	8.00	143		143	-119	167	0	0	167	50.350	-3.583	982	42.748	1916	-0.212	-4	56	12	56	80		-103	35			IHB 2131		
	Torquay	1852	12	6.49	6.33	49		143	-247	-55	0	0	-55	50.467	-3.533	982	47.465	1916	-0.204	13	59	12	29	67		-103	36	1852	1853	Tidal Ledger page 414		
	Torquay	1859	0.5	10.40	9.96		132		-247	-115	47	52	-16	50.467	-3.533	982	47.465	1916	-0.204	12	59	0	52	78		-103	37	28-Jun-1859	13-Jul-1859	OS 1859		OS
	Torquay	1896	0.5				115		-247	-132	0	0	-132	50.467	-3.533	982	47.465	1916	-0.204	4	59	0	79	99		-103	38			OS 1896		OS
	Torquay	1960	1	7.06	7.02		12			12	39	-47	3	50.467	-3.533	982	47.465	1916	-0.204	-9	59	0	36	69		-103	39	26-Jul-1960	30	IH 1059		
																											40					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
D	Exmouth	1960	1	5.99	6.00		-3			-3	22	-54	-36	50.620	-3.414	251	69.456	1916	-0.189	-8	71	0	19	73	1.489	-44	41	26-Jul-1960	30	IHB1061		
WEYMOUTH	Axmouth	1838	1	73.25	72.53	221		-16		205	-15	26	215	50.703	-3.056	251	46.456	1916	-0.162	13	58	12	44	74		-44	42	04-Jan-1838	02-Feb-1838	Bunt and Whewell	0	
	Axmouth	1838	0.5	71.96	72.53	-172		-16		-188	24	37	-127	50.703	-3.056	251	46.456	1916	-0.162	13	58	12	26	65		-44	43	16-Jul-1838	30-Jul-1838	Bunt and Whewell		
	Lyme Regis	1849	1	7.91	6.42	256		-16	-203	37	-74	4	-33	50.717	-2.933	251	39.004	1916	-0.154	10	53	12	36	65		-44	44	15-Nov-1849	15-Dec-1849	OS 1861		
	Lyme Regis	1960	1	6.61	6.30		94			94	22	-54	62	50.717	-2.933	251	39.004	1916	-0.154	-7	53	0	19	56		-44	45	26-Jul-1960	30	IHB 1062		
	Portland	1852	12	3.37	2.08	392		-16	-332	43	0	0	43	50.567	-2.433	251	0.000	1916	-0.128	8	9	12	15	21		-44	46	1852		Tidal Ledger page 332		
	Portland	1853	12	3.06	2.08	297		-16	-332	-51	0	0	-51	50.567	-2.433	251	0.000	1916	-0.128	8	9	12	15	21		-44	47	1853		Tidal Ledger page 332		
	Portland	1896	0.5				65		-332	-267	0	0	-267	50.567	-2.433	251	0.000	1916	-0.128	3	9	0	62	62		-44	48			OS 1896		
	Portland	1923	12	3.19	2.08	338		0	-332	5	-1	-27	-23	50.567	-2.433	251	0.000	1916	-0.128	-1	9	0	15	17		-44	49	01-Apr-1924	354	IHB 2 and ATT Table V		
	Portland	1968	12	3.29	3.19		32			32	-2	-4	25	50.567	-2.433	251	0.000	1916	-0.128	-7	9	0	15	17		-44	50	18-Jan-1968	18-Jan-1969	Tidal analysis 42		
	Weymouth	1859	0.5	5.04	4.48		171		-332	-161	28	51	-82	50.609	-2.448	1773	0.000	1916	-0.129	7	9	0	26	28		-129	51	27-Jun-1859	15-Jul-1859	OS 1859		OS
	Poole Harbour	1934	1	3.59	3.60	-3		0		-3	44	-20	22	50.714	-1.985	1878	7.725	1916	-0.105	-2	24	0	20	31		-82	52	19-Apr-1934	17-May-1934	IHB 2121		
	Poole Harbour	1964	1	3.67	3.60		21			21	-37	10	-6	50.714	-1.985	1878	7.725	1916	-0.105	-5	24	0	20	31		-82	53	20-Sep-1964	30	IHB 1117		
	Bournemouth	1963	1	4.10	3.60		152			152	-37	25	141	50.719	-1.881	1878	0.684	1916	-0.101	-5	9	0	20	22		-82	54	20-Sep-1963	30	IHB 1119		
																											55					
E	Southampton	1842	0.25	10.20	9.70	153		107	-222	38	35	-121	-48	50.900	-1.383	263	0.000	1916	-0.086	6	9	12	70	71	1.010	-59	56	23-Feb-1842	27-Feb-1842	Airy 1843		
SOUTHAMPTON	Southampton	1859	0.5	12.37	11.58		241		-222	19	12	7	38	50.900	-1.383	263	0.000	1916	-0.086	5	9	0	53	54		-59	57	26-Jul-1859	11-Aug-1859	OS 1859		OS
	Southampton	1913	12				177	0		177	0	-10	167	50.900	-1.383	263	0.000	1916	-0.086	0	9	0	22	24		-59	58	01-Jan-1913	31-Dec-1913	OS 1922		
	Southampton	1924	12	7.90	6.75		351	0	-222	129	0	-18	111	50.900	-1.383	263	0.000	1916	-0.086	-1	9	0	22	24		-59	59	01-Jan-1924	31-Dec-1924	Tidal Ledger and IHB 3		
	Southampton	1964	12	7.78	7.48		90			90	0	21	111	50.900	-1.383	263	0.000	1916	-0.086	-4	9	0	22	24		-59	60	01-Jan-1964	31-Dec-1964	Tidal analysis 50		
	Calshot	1924	12	6.96	6.75	64		107	-204	-33	0	0	-33	50.817	-1.300	2281	16.858	1916	-0.082	-1	35	12	22	43		-162	61	01-Jan-1924	31-Dec-1924	Tidal Ledger page 332		
																											62					
F	Portsmouth	1832	7	12.86	12.44	129		70	-232	-33	-24	13	-43	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	25	29	1.144	-112	63	01-Jun-1832	31-Dec-1832	Admiralty Survey Royal Society (1833)		
PORTSMOUTH	Portsmouth	1833	12	12.88	12.44	132		70	-232	-30	0	-9	-38	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	24	28		-112	64	01-Jan-1833	31-Dec-1833	Admiralty Survey Royal Society (1833)		
	Portsmouth	1834	12	12.78	12.44	104		70	-232	-58	0	27	-30	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	24	28		-112	65	01-Jan-1834	31-Dec-1834	Admiralty Survey HMSO (1835)		
	Portsmouth	1835	12	12.74	12.44	92		70	-232	-70	0	14	-56	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	24	28		-112	66	01-Jan-1835	31-Dec-1835	Admiralty Survey OS (1861a)		
	Portsmouth	1836	12	12.74	12.44	92		70	-232	-70	0	-11	-80	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	24	28		-112	67	01-Jan-1836	31-Dec-1836	Admiralty Survey OS (1861a)		
	Portsmouth	1837	12	12.74	12.44	92		70	-232	-70	0	8	-61	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	24	28		-112	68	01-Jan-1837	31-Dec-1837	Admiralty Survey OS (1861a)		
	Portsmouth	1838	12	12.74	12.44	92		70	-232	-70	0	7	-63	50.802	-1.111	350	0.000	1916	-0.076	6	9	12	24	28		-112	69	01-Jan-1838	31-Dec-1838	Admiralty Survey OS (1861a)		
	Portsmouth	1895	12	12.74	12.44	177		70	-232	15	0	-3	13	50.802	-1.111	350	0.000	1916	-0.076	2	9	12	24	28		-112	70	01-Jan-1895	31-Dec-1895	Admiralty Ledger page 332		
	Portsmouth	1914	12	6.89	6.17	219		70	-232	57	0	-40	18	50.802	-1.111	350	0.000	1916	-0.076	0	9	12	24	28		-112	71	01-Jan-1914	31-Dec-1914	Admiralty Ledger page 332		
	Portsmouth	1929	1	6.95	6.17	238		0	-232	6	29	2	37	50.802	-1.111	350	0.000	1916	-0.076	-1	9	0	32	33		-112	72	21-Jun-1929	29	IHB 2002		
	Portsmouth	1930	12	7.15	6.17	299		0	-232	67	0	-25	42	50.802	-1.111	350	0.000	1916	-0.076	-1	9	0	24	25		-112	73	01-Jan-1930	31-Dec-1930	IHB 99		
	Portsmouth	1962	12	7.14	6.80		103	0		103	0	4	108	50.802	-1.111	350	0.000	1916	-0.076	-3	9	0	24	25		-112	74	01-Jan-1962	365	Tidal analysis 44		
	Portsmouth	1975	12	2835	2730		105	0		105	0	34	139	50.802	-1.111	350	0.000	1916	-0.076	-4	9	0	24	25		-112	75	01-Jan-1975	31-Dec-1975	Tidal analysis 45		
	Selsey Bill	1963	1	9.66	9.52		43			43	36	-26	53	50.733	-0.783	350	24.305	1916	-0.063	-3	42	0	32	52		-112	76	06-Jun-1963	30	IH 1063		
	Bognor Regis	1959	1	8.14	8.00		43	0		43	53	2	98	50.783	-0.673	350	30.872	1916	-0.062	-3	47	0	33	58		-112	77	17-Mar-1959	30	IHB 1065		
																											78					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Cluster core station	Summary of all new data by cluster New data location	Year	Months	MTL or MSL ft or mm	TGZ or CD to OD ft or mm	MTL to OD mm	MSL to ODL mm	MTL to MSL mm	ODL or ODN1 to ODN3 mm	Level to ODN mm	seas. adjust mm	met. adjust mm	MSL to ODN mm	Lat (deg)	Long (deg)	PSMSL ref site ID	Dist. between sites (km)	ODN ref Year Fund. Levelling year	GIA mm/yr	GIA offset mm	Level. uncert. mm	MTL to MSL uncert. mm	Seas. uncert. mm	Quad. Total uncert. mm	SLR mm/yr	ODN offset mm	row No.	Start or centre date	End date or duration (days) date or days	Source	OW	Org
G	Shoreham	1849	4	9.25	8.08	357		-57	-187	113	-59	13	67	50.833	-0.250	1008	0.000	1916	-0.053	4	9	12	29	32	2.117	-70	79	01-Sep-1849	30-Dec-1849	Tidal Ledger page 382		
NEWHAVEN	Shoreham	1859	0.5	10.43	10.25		58		-187	-129	27	52	-50	50.833	-0.250	1008	0.000	1916	-0.053	3	9	0	42	42		-70	80	28-Jun-1859	13-Jul-1859	OS 1859		OS
	Shoreham	1896	0.5				217		-187	30	0	0	30	50.833	-0.250	1008	0.000	1916	-0.053	1	9	0	75	75		-70	81			OS 1896		OS
	Shoreham	1918	3	9.15	8.62	162		-57		105	0	0	105	50.833	-0.250	1008	0.000	1916	-0.053	0	9	12	37	40		-70	82	1918		Tidal Ledger page 382		
	Shoreham	1953	2				204			204	-48	12	168	50.833	-0.250	1008	0.000	1916	-0.053	-2	9	0	31	32		-70	83	01-Sep-1953	31-Oct-1953	Bowden 1956		
	Shoreham	1959	1	8.77	8.62		46			46	56	20	122	50.833	-0.250	1008	0.000	1916	-0.053	-2	9	0	42	43		-70	84	17-Mar-1959	30	IH 1121		
	Shoreham	2015	12	268	0		268			268	0	18	286	50.833	-0.250	1008	0.000	1916	-0.053	-5	9	0	26	27		-70	85	01-Jan-2015	31-Dec-2015	riverlevels.uk		
	Shoreham	2016	12	207	0		207			207	0	2	209	50.833	-0.250	1008	0.000	1916	-0.053	-5	9	0	26	27		-70	86	01-Jan-2016	31-Dec-2016	riverlevels.uk		
	Shoreham	2017	12	228	0		228			228	0	-2	227	50.833	-0.250	1008	0.000	1916	-0.053	-5	9	0	26	27		-70	87	01-Jan-2017	31-Dec-2017	riverlevels.uk		
	Shoreham	2018	12	146	0		146			146	0	2	148	50.833	-0.250	1008	0.000	1916	-0.053	-5	9	0	26	27		-70	88	01-Jan-2018	31-Dec-2018	riverlevels.uk		
	Newhaven	1936	2	10.48	10.40		24		-43	-18	56	-7	30	50.782	0.057	1548	0.000	1916	-0.042	-1	9	0	42	43		-143	89	15-Mar-1936	29	IHB 2132		
	Newhaven	1956	12	10.44	10.32		37		-43	-6	0	7	1	50.782	0.057	1548	0.000	1916	-0.042	-2	9	0	26	27		-143	90	15-Mar-1956	365	IHB 1375		
	Newhaven	1957	12	14.54	14.32		68		-43	25	0	14	40	50.782	0.057	1548	0.000	1916	-0.042	-2	9	0	26	27		-143	91	01-Jan-1957	365	tidal analysis 39		
	Newhaven	1959	1	10.63	10.40		71		-43	29	56	19	104	50.782	0.057	1548	0.000	1916	-0.042	-2	9	0	42	43		-143	92	17-Mar-1959	30	tidal analysis 40		
	Newhaven	1982	12	5212	5020		192			192	0	-16	177	50.782	0.057	1548	0.000	1916	-0.042	-3	9	0	26	27		-143	93	26-May-1982	25-May-1983	tidal analysis 40		
	Eastbourne	1959	1	10.669	10.53		42			42	56	19	118	50.769	0.285	1548	16.063	1916	-0.034	-1	34	0	42	54		-143	94	17-Mar-1959	30	IHB 1069		
	Hastings	1924		11.40	11.00	122		-57		65	0	0	65	50.854	0.573	1548	37.154	1916	-0.034	0	52	12	53	75		-143	95	1924		Tidal Ledger page 159		
	Hastings	1963	1	11.15	11.00		46			46	38	-25	59	50.854	0.573	1548	37.154	1916	-0.034	-2	52	0	32	61		-143	96	06-Jun-1963	30	IHB 1070		
																											97					
H	Folkestone	1934	1	9.86	9.00	262			-366	-104	54	-6	-56	51.081	1.170	255	11.307	1916	-0.046	-1	29	0	38	48	2.259	-189	98	21-Apr-1934	19-May-1934	IHB 2121		
DOVER	Dover	1859	0.5	11.82	11.40		127		-338	-211	-1	2	-210	51.114	1.323	255	0.000	1916	-0.047	3	9	0	59	60		-189	99	20-Jul-1859	12-Aug-1859	OS 1859		
	Dover	1883	12	9.16	8.67	150			-338	-188	-1	-4	-193	51.114	1.323	255	0.000	1916	-0.047	2	9	0	29	30		-189	100	01-Jan-1883	31-Dec-1883	Darwin/Roberts 1916		
	Dover	1884	12	9.11	8.67	135			-338	-203	-1	-2	-207	51.114	1.323	255	0.000	1916	-0.047	2	9	0	29	30		-189	101	01-Jan-1884	31-Dec-1884	Darwin/Roberts 1916		
	Dover	1896	0.5				162		-338	-176	0	0	-176	51.114	1.323	255	0.000	1916	-0.047	1	9	0	91	92		-189	102			OS 1896		OS
	Dover	1902	2	8.92	8.40	157		-24	-338	-205	54	-15	-165	51.114	1.323	255	0.000	1916	-0.047	1	9	12	41	43		-189	103	01-Apr-1902	31-May-1902			
	Dover	1903	3	8.90	8.40	151		-24	-338	-211	46	-7	-172	51.114	1.323	255	0.000	1916	-0.047	1	9	12	30	33		-189	104	01-Apr-1903	30-Jun-1903			
	Dover	1910	12	8.96	8.42	165			-338	-173	-1	3	-172	51.114	1.323	255	0.000	1916	-0.047	0	9	0	29	30		-189	105	01-Oct-1910	30-Sep-1911	Roberts ATT 1919		
	Dover	1915	12	9.34	8.42	280		-24	-338	-82	0	0	-82	51.114	1.323	255	0.000	1916	-0.047	0	9	12	29	32		-189	106	1915	1916			
	Dover	1960	12	9.82	9.71		33	0		33	-1	-9	22	51.114	1.323	255	0.000	1916	-0.047	-2	9	0	29	30		-189	107	01-Jul-1960	365	Tidal analysis 12		
	Dover	1974	12	3695	3670		25	0		25	-1	-7	18	51.114	1.323	255	0.000	1916	-0.047	-3	9	0	29	30		-189	108	15-Jun-1974	19-Jun-1975	Tidal analysis 12		
	Ramsgate	1855	12	8.04	7.08	293		-24	-405	-137	0	0	-137	51.333	1.417	992	0.000	1916	-0.078	5	9	12	29	32		-135	109			Tidal Ledger page 354 and IHB 5		
	Ramsgate	1859	2	10.55	9.58	297		-24	-405	-133	0	0	-133	51.333	1.417	992	0.000	1916	-0.078	4	9	12	36	39		-135	110			OS FGL - date uncertain		
	Ramsgate	1957	12				37			37	-1	9	45	51.333	1.417	992	0.000	1916	-0.078	-3	9	0	29	30		-135	111	04-Jan-1957	31-Dec-1957	Cartwright and Crease 1963		
	Ramsgate	1958	12				37			37	-1	-3	34	51.333	1.417	992	0.000	1916	-0.078	-3	9	0	29	30		-135	112	01-Jan-1958	28-Dec-1958	Cartwright and Crease 1963		
	Ramsgate	1963	12	12.85	12.90		-17	0		-17	-1	10	-8	51.333	1.417	992	0.000	1916	-0.078	-4	9	0	29	30		-135	113	01-Jul-1963	365	Tidal analysis 45		
	Margate	1934	1	6.93	7.20		-82			-82	35	7	-40	51.400	1.400	1225	0.000	1916	-0.088	-2	9	0	40	41		-97	114	24-May-1934	21-Jun-1934	IHB 2121		
	Margate	1967	12	8.55	8.20		105			105	-1	-5	99	51.400	1.400	1225	0.000	1916	-0.088	-4	9	0	29	30		-97	115	10-Nov-1967	365	Tidal analysis 35		
																											116					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
I	Sheerness	1827	12	17.23	15.87	415		-101	-505	-191	-1	2	-190	51.446	0.743	3	0.000	1916	-0.094	8	9	12	37	40	1.903	-107	117	01-Jan-1827	31-Dec-1827	Lloyd 1832		
SHEERNESS	Sheerness	1828	12	17.31	15.87	437		-103	-505	-171	-1	-1	-172	51.446	0.743	3	0.000	1916	-0.094	8	9	12	37	40		-107	118	01-Jan-1828	31-Dec-1828	Lloyd 1832		
	Sheerness	1829	12	17.30	15.87	434		-104	-505	-175	-1	6	-169	51.446	0.743	3	0.000	1916	-0.094	8	9	12	37	40		-107	119	01-Jan-1829	31-Dec-1829	Lloyd 1832		
	Sheerness	1832	12	17.40	15.87	467		-99	-505	-137	-1	6	-131	51.446	0.743	3	0.000	1916	-0.094	8	9	12	37	40		-107	120	01-Jan-1832	31-Dec-1832	Admiralty Survey Royal Society (1833)		
	Sheerness	1836	12	17.46	15.87	484		-84	-505	-105	-1	-21	-127	51.446	0.743	3	0.000	1916	-0.094	8	9	12	37	40		-107	121	01-Jan-1836	31-Dec-1836	Commissioners report 1845		
	Sheerness	1837	12	17.55	15.87	513		-82	-505	-74	-1	-2	-77	51.446	0.743	3	0.000	1916	-0.094	7	9	12	37	40		-107	122	01-Jan-1837	31-Dec-1837	Commissioners report 1845		
	Sheerness	1838	12	17.46	15.87	484		-81	-505	-102	-1	-15	-117	51.446	0.743	3	0.000	1916	-0.094	7	9	12	37	40		-107	123	01-Jan-1838	31-Dec-1838	Commissioners report 1845		
	Sheerness	1839	12	17.46	15.87	484		-81	-505	-102	-1	-6	-108	51.446	0.743	3	0.000	1916	-0.094	7	9	12	37	40		-107	124	01-Jan-1839	31-Dec-1839	Commissioners report 1845		
	Sheerness	1859	0.5	11.52	10.07		441		-505	-64	-14	1	-76	51.446	0.743	3	0.000	1916	-0.094	5	9	0	74	74		-107	125	28-Jul-1859	11-Aug-1859	OS 1859		OS
	Sheerness	1870	12	17.84	17.94	-31		-96		-127	-1	-10	-137	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	126	01-Jan-1870	31-Dec-1870	Tidal register		
	Sheerness	1871	12	17.96	17.94	7		-92		-85	-1	-3	-88	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	127	01-Jan-1871	31-Dec-1871	Tidal register		
	Sheerness	1872	12	17.45	17.44	4		-88		-85	-1	-1	-86	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	128	01-Jan-1872	31-Dec-1872	Tidal register		
	Sheerness	1873	12	17.14	17.44	-91		-85		-176	-1	-10	-187	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	129	01-Jan-1873	31-Dec-1873	Tidal register		
	Sheerness	1874	12	17.18	17.44	-79		-82		-161	-1	-11	-173	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	130	01-Jan-1874	31-Dec-1874	Tidal register		
	Sheerness	1875	12	17.44	17.44	1		-81		-81	-1	-4	-85	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	131	01-Jan-1875	31-Dec-1875	Tidal register		
	Sheerness	1876	12	17.40	17.44	-12		-81		-94	-1	-11	-105	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	132	01-Jan-1876	31-Dec-1876	Tidal register		
	Sheerness	1877	11	17.30	17.44	-42		-82		-124	-1	-8	-133	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	133	01-Jan-1877	31-Dec-1877	Tidal register		
	Sheerness	1878	12	17.49	17.44	15		-85		-70	-1	-23	-93	51.446	0.743	3	0.000	1916	-0.094	4	9	12	37	40		-107	134	01-Jan-1878	31-Dec-1878	Tidal register		
	Sheerness	1879	12	17.32	17.44	-38		-88		-126	-1	-9	-135	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	135	01-Jan-1879	31-Dec-1879	Tidal register		
	Sheerness	1880	12	17.36	17.44	-25		-92		-117	-1	-12	-130	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	136	01-Jan-1880	31-Dec-1880	Tidal register		
	Sheerness	1881	12	17.34	17.44	-31		-96		-126	-1	-3	-130	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	137	01-Jan-1881	31-Dec-1881	Tidal register		
	Sheerness	1882	6	17.55	17.44	33		-99		-67	-33	-12	-112	51.446	0.743	3	0.000	1916	-0.094	3	9	12	41	43		-107	138	01-Jul-1882	31-Dec-1882	Tidal register		
	Sheerness	1883	12	17.98	17.94	12		-102		-90	-1	-2	-92	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	139	01-Jan-1883	31-Dec-1883	Tidal register		
	Sheerness	1884	12	18.12	17.94	54		-104		-49	-1	-9	-59	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	140	01-Jan-1884	31-Dec-1884	Tidal register		
	Sheerness	1885	12	17.98	17.94	12		-104		-91	-1	-8	-101	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	141	01-Jan-1885	31-Dec-1885	Tidal register		
	Sheerness	1886	12	17.89	17.94	-15		-103		-118	-1	-7	-125	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	142	01-Jan-1886	31-Dec-1886	Tidal register		
	Sheerness	1887	12	17.92	17.94	-7		-101		-108	-1	-18	-127	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	143	01-Jan-1887	31-Dec-1887	Tidal register		
	Sheerness	1888	12	17.83	17.94	-32		-98		-130	-1	-3	-134	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	144	01-Jan-1888	31-Dec-1888	Tidal register		
	Sheerness	1889	12	18.10	17.94	49		-94		-46	-1	-12	-58	51.446	0.743	3	0.000	1916	-0.094	3	9	12	37	40		-107	145	01-Jan-1889	31-Dec-1889	Tidal register		
	Sheerness	1890	12	17.92	17.94	-7		-91		-98	-1	0	-98	51.446	0.743	3	0.000	1916	-0.094	2	9	12	37	40		-107	146	01-Jan-1890	31-Dec-1890	Tidal register		
	Sheerness	1891	12	18.05	17.94	32		-87		-55	-1	10	-46	51.446	0.743	3	0.000	1916	-0.094	2	9	12	37	40		-107	147	01-Jan-1891	31-Dec-1891	Tidal register		
	Sheerness	1896	0.5				476		-494	-18	0	0	-18	51.446	0.743	3	0.000	1916	-0.094	2	9	0	87	87		-107	148			OS 1896		OS
	Sheerness	1930	12	17.88	17.44	135		-91		44	-1	0	43	51.446	0.743	3	0.000	1916	-0.094	-1	9	12	37	40		-107	149	01-Jan-1930	31-Dec-1930	Tidal register		
	Sheerness	1969	12	9.86	9.50		110			110	0	-16	93	51.446	0.743	3	0.000	1916	-0.094	-5	9	0	37	38		-107	150	06-Nov-1969	365	Tideal analysis 49		
	Gravesend	1842	12	10.54	10.47	22		-91	0	-69	-1	-6	-76	51.445	0.387	335	2.777	1916	-0.092	7	14	12	37	42		-39	151	01-Jan-1842	31-Dec-1842	Redman 1877		
	Gravesend	1843	12	10.71	10.47	73		-91	0	-18	-1	-2	-21	51.445	0.387	335	2.777	1916	-0.092	7	14	12	37	42		-39	152	01-Jan-1843	31-Dec-1843	Redman 1877		
	Gravesend	1844	12	10.71	10.47	73		-91	0	-18	-1	-18	-37	51.445	0.387	335	2.777	1916	-0.092	7	14	12	37	42		-39	153	01-Jan-1844	31-Dec-1844	Redman 1877		
	Gravesend	1845	2	10.71	10.47	73		-91	0	-18	26	-1	7	51.445	0.387	335	2.777	1916	-0.092	7	14	12	52	55		-39	154	01-Jan-1845	28-Feb-1845	Redman 1877		
	Southend	1911	12	9.28	7.47	552		-138	-479	-65	-1	-6	-71	51.514	0.724	334	0.000	1916	-0.101	1	9	12	37	40		-102	155	01-Jan-1911	31-Dec-1911	Tidal Ledger page 378		
	Southend	1925	12	8.96	7.47		453		-479	-25	-1	-4	-30	51.514	0.724	334	0.000	1916	-0.101	-1	9	0	37	38		-102	156	01-Jan-1925	31-Dec-1925	IHB 7		
	Southend	1961	12	20.32	20.00		98			98	-1	8	106	51.514	0.724	334	0.000	1916	-0.101	-5	9	0	37	38		-102	157	01-Jul-1961	365	Tidal analysis 51		
																											158					
J	Walton	1968	12	7.14	7.10		13			13	1	-11	3	51.848	1.268	1224	0.212	1916	-0.153	-8	9	0	19	20	1.508	-154	159	26-Sep-1967	25-Sep-1968	Tidal analysis 59		
FELIXSTOWE	Harwich	1859	0.5	13.15	11.27		574		-610	-36	-12	-2	-50	51.948	1.292	742	0.000	1916	-0.168	10	9	0	40	41		0	160	28-Jul-1859	16-Aug-1859	OS 1859		
	Harwich	1896	0.5				505		-610	-105	0	0	-105	51.948	1.292	742	0.000	1916	-0.168	3	9	0	82	82		0	161			OS 1896		OS
	Harwich	1931	12	6.66	6.58		24			24	1	7	32	51.948	1.292	742	0.000	1916	-0.168	-3	9	0	19	20		0	162	01-Nov-1931	365	IHB 74		
	Harwich	1954	12	6.71	6.62		28			28	1	3	32	51.948	1.292	742	0.000	1916	-0.168	-6	9	0	19	20		0	163	28-Mar-1954	365	Tidal analysis 20		
	Felixstowe	1902	12	6.79	6.59	61		-75		-14	1	3	-11	51.958	1.347	214	0.000	1916	-0.171	2	9	12	19	24		-119	164	01-Jan-1902	31-Dec-1902	Tidal Ledger page 174		
	Felixstowe	1931	12	6.66	4.59	630		0	-610	21	1	8	29	51.958	1.347	214	0.000	1916	-0.171	-3	9	0	19	20		-119	165	01-Nov-1931	365	IHB 74		
																											166					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
K	Lowestoft	1848	12	3.56	2.25	399		42	-506	-65	0	0	-65	52.473	1.750	754	0.000	1916	-0.274	19	9	12	28	31	1.926	-145	167			Tidal Ledger page 247		
LOWESTOFT	Lowestoft	1852	1	3.85	2.32	466		42	-506	2	-23	-11	-32	52.473	1.750	754	0.000	1916	-0.274	18	9	12	45	47		-145	168	24-Aug-1852	29	IHB 2132		
	Lowestoft	1859	0.5	10.57	9.18		421		-506	-85	-11	2	-93	52.473	1.750	754	0.000	1916	-0.274	16	9	0	64	64		-145	169	26-Jul-1859	17-Aug-1859	OS 1859		OS
	Lowestoft	1896	0.5				478		-506	-28	0	0	-28	52.473	1.750	754	0.000	1916	-0.274	5	9	0	54	55		-145	170			OS 1896		OS
	Lowestoft	1927	12	3.79	2.25	460		42	-506	-4	0	0	-4	52.473	1.750	754	0.000	1916	-0.274	-3	9	12	28	31		-145	171	01-Jan-1927	31-Dec-1927	Tidal Ledger page 248		
	Lowestoft	1965	12	15.23	15.01		66	0		66	0	-13	52	52.473	1.750	754	0.000	1916	-0.274	-13	9	0	28	29		-145	172	01-Jul-1965	365	Tidal analysis 33		
	Gorleston	1942	12	3.89	4.22		-101	0		-101	0	5	-96	52.571	1.734	754	10.894	1916	-0.290	-8	28	0	28	39		-145	173	01-Jan-1942	31-Dec-1942	IHB 845		
	G Yarmouth	1927	12	3.96	4.10	-43		42		-1	0	0	0	52.584	1.736	754	12.324	1916	-0.292	-3	30	12	28	42		-145	174	01-Jan-1927	31-Dec-1927	Tidal Ledger page 486		
	Caister	1954	1	4.47	4.42	15		0		15	29	-9	35	52.649	1.724	754	19.591	1916	-0.303	-12	38	0	34	50		-145	175	17-Jun-1954	30	IHB2237		
	Cromer	1947	1	8.38	6.30		634	0	-506	128	-40	4	92	52.934	1.302	1632	0.000	1916	-0.303	-9	9	0	47	48		-100	176	15-Sep-1947	30	IHB 2200		
																											177					
L	Skegness	1916	12	9.93	8.70	375		29	-216	187	0	0	187	53.144	0.336	286	64.297	1916	-0.198	0	68	12	22	73	1.546	71	178	1916	1917	Tidal Ledger page 382		
IMMINGHAM	Sutton on Sea	1881	2			557		29	-488	98	15	-6	107	53.312	0.281	286	47.050	1916	-0.188	7	58	12	27	65		71	179	28-Jun-1881	09-Aug-1881	Wallis, T. 1899		
	Grimsby	1912	12	10.72	8.83	576		29	-488	117	0.609	-4	114	53.583	0.070	286	17.795	1916	-0.141	1	36	12	22	44		71	180	01-Jan-1912	31-Dec-1912	Tidal Ledger page 151		
	Grimsby	1864	1	16.61	15.00	489		29	-488	31	53	-14	70	53.583	0.070	286	17.795	1916	-0.141	7	36	12	30	48		71	181	09-May-1864	06-Jun-1864	Shelford 1869		
	Grimsby	1859	0.5	16.82	15.00		553		-488	65	9	7	81	53.583	0.070	286	17.795	1916	-0.141	8	36	0	38	52		71	182	19-Jul-1859	05-Aug-1859	OS 1859		OS
	Immingham	1912	12	11.35	9.25	640		29	-400	269	1	-5	266	53.630	-0.187	286	0.000	1916	-0.089	0	9	12	22	26		71	183	01-Jan-1912	24-Dec-1912	Tidal Ledger page 209		
	Immingham	1926	12	11.30	9.25		625	0	-400	225	1	-3	223	53.630	-0.187	286	0.000	1916	-0.089	-1	9	0	22	24		71	184	01-Jan-1926	24-Dec-1926	IHB 8		
	Immingham	1956	12	11.66	9.25		734		-400	334	1	-3	332	53.630	-0.187	286	0.000	1916	-0.089	-4	9	0	22	24		71	185	12-Mar-1956	365	IHB 915		
	Immingham	1966	12	38.63	37.69		286	0		286	1	-12	275	53.630	-0.187	286	0.000	1916	-0.089	-4	9	0	22	24		71	186	29-Dec-1966	365	Tidal analysis 26		
	Immingham	1969	12	38.55	37.68		264	0		264	1	-8	257	53.630	-0.187	286	0.000	1916	-0.089	-5	9	0	22	24		71	187	01-Dec-1969	365	Tidal analysis 26		
	Immingham	1976	12	11720	11480		240			240	1	13	253	53.630	-0.187	286	0.000	1916	-0.089	-5	9	0	22	24		71	188	01-Jun-1975	31-May-1976	Tidal analysis 27		
	Hull	1851	3	15.40	14.71		210		-201	9	-9	1	1	53.741	-0.340	286	15.866	1916	-0.048	3	34	0	25	42		71	189	01-Jul-1851	30-Sep-1851	OS 1859		
	Hull	1862	1	16.05	14.71		409		-201	208	11	-15	204	53.741	-0.340	286	15.866	1916	-0.048	3	34	0	27	43		71	190	09-Jul-1862	10-Aug-1862			
	Hull	1864	1	15.35	14.71		196		-201	-5	53	-14	34	53.741	-0.340	286	15.866	1916	-0.048	2	34	0	30	45		71	191	09-May-1864	06-Jun-1864	Shelford 1869		
	Hull	1896	0.5				318		-201	117	0	0	117	53.741	-0.340	286	15.866	1916	-0.048	1	34	0	47	58		71	192					
	Hull	1912	12	11.60	10.08	463		29	-183	309	1	-4	306	53.741	-0.340	286	15.866	1916	-0.048	0	34	12	22	42		71	193	01-Jan-1912	31-Dec-1912	IHB 15?		
	Hull	1961	12	11.67	10.68		300			300	1	1	302	53.741	-0.340	286	15.866	1916	-0.048	-2	34	0	22	40		71	194	01-Jul-1961	365	IHB 1071		
	Hull	1977	12	4162	3900		262			262	1	-5	258	53.741	-0.340	286	15.866	1916	-0.048	-3	34	0	22	40		71	195	01-Nov-1976	31-Oct-1977	PSMSL		
	Hull	1978	11	4122	3900		222			222	7	-11	218	53.741	-0.340	286	15.866	1916	-0.048	-3	34	0	22	41		71	196	01-Nov-1977	30-Sep-1978	PSMSL		
																											197					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
M	Scarborough	1848	?	9.06	8.30	232		-25	-79	127	0	0	127	54.283	-0.383	946	0.000	1916	0.048	-3	9	12	38	41	2.558	23	198			Tidal Ledger page 383		
WHITBY	Scarborough	1859	0.5	10.78	10.45		102		-79	23	5	-5	22	54.283	-0.383	946	0.000	1916	0.048	-3	9	0	29	30		23	199	01-Aug-1859	19-Aug-1859	OS 1859		OS
	Scarborough	1965	12	9.36	8.60		232			232	0	-6	225	54.283	-0.383	946	0.000	1916	0.048	2	9	0	17	19		23	200	01-Jan-1965	31-Dec-1965	IHB 1378		
	Scarborough	2006	12	306	0		306			306	0	-2	303	54.283	-0.383	946	0.000	1916	0.048	4	9	0	17	19		23	201	01-Jan-2006	31-Dec-2006	CCO		
	Scarborough	2014	12	349	0		349			349	0	-1	348	54.283	-0.383	946	0.000	1916	0.048	5	9	0	17	19		23	202	01-Jan-2014	31-Dec-2014	CCO		
	Scarborough	2015	12	343	0		343			343	0	-5	338	54.283	-0.383	946	0.000	1916	0.048	5	9	0	17	19		23	203	01-Jan-2015	31-Dec-2015	CCO		
	Scarborough	2016	12	363	0		363			363	0	3	366	54.283	-0.383	946	0.000	1916	0.048	5	9	0	17	19		23	204	01-Jan-2016	31-Dec-2016	CCO		
	Scarborough	2017	12	357	0		357			357	0	-8	349	54.283	-0.383	946	0.000	1916	0.048	5	9	0	17	19		23	205	01-Jan-2017	31-Dec-2017	CCO		
	Scarborough	2018	12	347	0		347			347	0	10	356	54.283	-0.383	946	0.000	1916	0.048	5	9	0	17	19		23	206	01-Jan-2018	31-Dec-2018	CCO		
	Whitby	1932	1	8.43	8.00		131			131	69	-27	173	54.490	-0.615	1505	0.000	1916	0.153	2	9	0	17	19		104	207	01-May-1932	29-May-1932	IHB 2122		
	Whitby	1980	1	3471	3295		176			176	59	13	248	54.490	-0.615	1505	0.000	1916	0.153	10	9	0	17	19		104	208	16-May-1980	13-Jun-1980	Tidal analysis 187		
	Whitby	1980	1	3582	3295		287			287	-33	-10	244	54.490	-0.615	1505	0.000	1916	0.153	10	9	0	21	23		104	209	31-Aug-1980	28-Sep-1980	Tidal analysis 187		
	Whitby II	2014	12	300	0		300			300	0	-1	299	54.490	-0.615	1505	0.000	1916	0.153	15	9	0	17	19		104	210	01-Jan-2014	31-Dec-2014	Channel Coastal Observatory		
	Whitby II	2015	12	312	0		312			312	0	-5	307	54.490	-0.615	1505	0.000	1916	0.153	15	9	0	17	19		104	211	01-Jan-2015	31-Dec-2015	Channel Coastal Observatory		
	Whitby II	2016	12	324	0		324			324	0	3	327	54.490	-0.615	1505	0.000	1916	0.153	15	9	0	17	19		104	212	01-Jan-2016	31-Dec-2016	Channel Coastal Observatory		
	Whitby II	2017	12	344	0		344			344	0	-8	336	54.490	-0.615	1505	0.000	1916	0.153	15	9	0	17	19		104	213	01-Jan-2017	31-Dec-2017	Channel Coastal Observatory		
	Whitby II	2018	12	314	0		314			314	0	9	323	54.490	-0.615	1505	0.000	1916	0.153	16	9	0	17	19		104	214	01-Jan-2018	31-Dec-2018	Channel Coastal Observatory		
	Tees Entrance	1897	12	8.96	8.40	171		-25	15	161	0	4	165	54.647	-1.138	1505	37.976	1916	0.362	-7	52	12	17	56		104	215	01-Jan-1897	31-Dec-1897	Tidal Ledger page 412		
	Tees Entrance	1948	12	9.10	8.10	305		-25		280	0	3	283	54.647	-1.138	1505	37.976	1916	0.362	12	52	12	17	56		104	216	01-Jan-1948	31-Dec-1948	ATT		
	Hartlepool	1846	12	8.66	8.31	107		-5	61	163	0	0	163	54.700	-1.200	1505	44.351	1916	0.399	-28	57	12	17	60		104	217			Tidal Ledger page 174		
	Hartlepool	1847	12	8.66	8.31	107		-5	61	163	0	0	163	54.700	-1.200	1505	44.351	1916	0.399	-28	57	12	17	60		104	218			Tidal Ledger page 174		
	Hartlepool	1848	12	8.66	8.31	107		-5	61	163	0	0	163	54.700	-1.200	1505	44.351	1916	0.399	-27	57	12	17	60		104	219			Tidal Ledger page 174		
	Hartlepool	1896	0.5				-6		61	55	0	0	55	54.700	-1.200	1505	44.351	1916	0.399	-8	57	0	54	78		104	220			OS 1896		OS
	Hartlepool	1981	11	7101	6794		307			307	-3	-6	298	54.700	-1.200	1505	44.351	1916	0.399	26	57	0	17	59		104	221	31-Mar-1981	16-Feb-1983	Tidal analysis 60		
	West Hartlepool	1858	12	12.15	12.00		46	0	61	107	0	-2	105	54.700	-1.200	1505	44.351	1916	0.399	-23	57	0	17	59		104	222	01-Jul-1858	30-Jun-1859	BAAS		
	West Hartlepool	1859	12	11.97	12.00		-9	0	61	52	0	-11	41	54.700	-1.200	1505	44.351	1916	0.399	-23	57	0	17	59		104	223	01-Jul-1859	30-Jun-1860	BAAS		
	West Hartlepool	1860	12	12.01	12.00		2	0	61	63	0	12	75	54.700	-1.200	1505	44.351	1916	0.399	-22	57	0	17	59		104	224	01-Jul-1860	05-Jul-1861	BAAS		
																											225					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/y	mm	No.	date	date or days			
N	Sunderland	1819	1	7.25	6.90	107		-4	61	164	0	0	164	54.917	-1.367	95	11.121	1916	0.521	-51	28	12	57	65	2.096	140	226	1819		Rennie 1819, BAAS 1878		
NORTH SHIELDS	Sunderland	1846	12	8.17	7.58	180			61	241	0	0	241	54.917	-1.367	95	11.121	1916	0.521	-36	28	0	29	40		140	227	1846	1847	Tidal Ledger page 383		
	Sunderland	1847	12	8.05	7.34	218			61	279	0	4	282	54.917	-1.367	95	11.121	1916	0.521	-36	28	0	29	40		140	228	01-Jan-1847	31-Dec-1847	OS 1859		
	North Shields	1813	1.7	7.53	6.91	189		-4		185	71	-12	244	55.007	-1.440	95	0.000	1916	0.576	-59	9	12	35	38		140	229	22-Apr-1813	11-Jun-1813	Brooke 1867		
	North Shields	1854	1	8.05	6.58	448		-4	-112	332	-74	-44	214	55.007	-1.440	95	0.000	1916	0.576	-36	9	12	52	54		140	230	01-Dec-1854	31-Dec-1854	Tyne. Comm. Rpt. 1855		
	North Shields	1855	12	7.57	6.58	302		-4	-112	186	0	6	191	55.007	-1.440	95	0.000	1916	0.576	-35	9	12	29	32		140	231	01-Jan-1855	31-Dec-1855	OS 1862		
	North Shields	1962	12	7.77	6.91		261	0		261	0	-2	259	55.007	-1.440	95	0.000	1916	0.576	26	9	0	29	30		140	232	01-Jul-1962	365	IHB 1122		
	Tyne Bar	1848	1	14.03	13.25	240		53	-112	181	0	0	181	55.012	-1.424	95	1.098	1916	0.571	-39	9	12	57	59		140	233			Tyne. Comm. Rpt. 1855		
	Tyne Bar	1849	2	14.02	13.25	235		53	-112	176	0	0	176	55.012	-1.424	95	1.098	1916	0.571	-38	9	12	45	47		140	234			Tyne. Comm. Rpt. 1855		
	Tyne Bar	1850	2	13.69	13.25	136		53	-112	77	0	0	77	55.012	-1.424	95	1.098	1916	0.571	-38	9	12	45	47		140	235			Tyne. Comm. Rpt. 1855		
	Tyne Bar	1851	2	14.09	13.25	257		53	-112	198	0	0	198	55.012	-1.424	95	1.098	1916	0.571	-37	9	12	45	47		140	236			Tyne. Comm. Rpt. 1855		
	Tyne Bar	1852	2	14.01	13.25	231		53	-112	172	0	0	172	55.012	-1.424	95	1.098	1916	0.571	-37	9	12	45	47		140	237			Tyne. Comm. Rpt. 1855		
	Tyne Bar	1853	2	13.49	13.25	73		53	-112	14	0	0	14	55.012	-1.424	95	1.098	1916	0.571	-36	9	12	45	47		140	238			Tyne. Comm. Rpt. 1855		
	Tyne Bar	1854	2	13.90	13.25	199		53	-112	140	0	0	140	55.012	-1.424	95	1.098	1916	0.571	-35	9	12	45	47		140	239			Tyne. Comm. Rpt. 1855		
	Tynemouth	1896	0.5				-65	-4	152	83	0	0	83	55.017	-1.400	95	2.736	1916	0.563	-11	14	12	81	83		140	240			OS 1896		OS
	Tynemouth	1929	12	7.64	7.08	171		-4	73	240	0	5	244	55.017	-1.400	95	2.736	1916	0.563	7	14	12	29	34		140	241	01-Jan-1929	31-Dec-1929	Tidal Ledger page		
	Tynemouth	1930	1	8.08	6.91	358		-4		354	4	-26	332	55.017	-1.400	95	2.736	1916	0.563	8	14	12	42	46		140	242	01-Aug-1930	31-Aug-1930			
	Tynemouth	1937	1	8.04	6.91	345		-4		341	-74	35	302	55.017	-1.400	95	2.736	1916	0.563	12	14	12	52	55		140	243	01-Dec-1937	31-Dec-1937			
	Tynemouth	1947	12	7.64	6.91		223	0		223	0	19	241	55.017	-1.400	95	2.736	1916	0.563	17	14	0	29	32		140	244	01-Jan-1947	31-Dec-1947	PSMSL		
	Tynemouth	1951	12	7.74	6.91		253	0		253	0	-15	238	55.017	-1.400	95	2.736	1916	0.563	20	14	0	29	32		140	245	01-Jan-1951	31-Dec-1951	PSMSL		
	Tynemouth	1955	12	7.79	6.91		268	0		268	0	8	275	55.017	-1.400	95	2.736	1916	0.563	22	14	0	29	32		140	246	01-Jan-1955	31-Dec-1955	PSMSL		
	Tynemouth	1956	12	7.66	6.91		228	0		228	0	11	238	55.017	-1.400	95	2.736	1916	0.563	23	14	0	29	32		140	247	01-Jan-1956	31-Dec-1956	PSMSL		
	Blyth	1951	1	7.45	6.49		293			293	4	-31	266	55.117	-1.483	769	0.000	1916	0.625	22	9	0	42	42		115	248	16-Aug-1951	30	IHB 2225		
	Blyth	2013	12	286	0		286			286	0	6	292	55.117	-1.483	769	0.000	1916	0.625	61	9	0	29	30		115	249	01-Jan-2013	31-Dec-2013	riverlevels.uk		
	Blyth	2014	12	330	0		330			330	0	-7	324	55.117	-1.483	769	0.000	1916	0.625	61	9	0	29	30		115	250	01-Jan-2014	31-Dec-2014	riverlevels.uk		
	Blyth	2015	12	347	0		347			347	0	-7	340	55.117	-1.483	769	0.000	1916	0.625	62	9	0	29	30		115	251	01-Jan-2015	31-Dec-2015	riverlevels.uk		
	Blyth	2016	12	361	0		361			361	0	3	364	55.117	-1.483	769	0.000	1916	0.625	63	9	0	29	30		115	252	01-Jan-2016	31-Dec-2016	riverlevels.uk		
	Blyth	2017	12	379	0		379			379	0	-8	371	55.117	-1.483	769	0.000	1916	0.625	63	9	0	29	30		115	253	01-Jan-2017	31-Dec-2017	riverlevels.uk		
	Blyth	2018	12	338	0		338			338	0	6	343	55.117	-1.483	769	0.000	1916	0.625	64	9	0	29	30		115	254	01-Jan-2018	31-Dec-2018	riverlevels.uk		
																											255					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
O	Berwick	1859	0.5	17.26	16.87		119		49	168	8	11	187	55.766	-2.009	190	41.421	1916	1.043	-59	55	0	37	66	2.130	173	256	11-Aug-1859	29-Aug-1859	OS 1859		OS
LEITH	Berwick	1896	0.5				119		49	168	0	0	168	55.766	-2.009	190	41.421	1916	1.043	-21	55	0	55	78		173	257			OS 1896		OS
	Berwick	1932	1	8.35	8.23	37				37	23	-6	54	55.766	-2.009	190	41.421	1916	1.043	17	55	0	30	62		173	258	16-Jun-1932	13-Jul-1932	IHB 2122		
	Dunbar	1856	?	9.64	8.90	226		-31	12	207	0	0	207	56.006	-2.517	190	0.000	1916	1.344	-81	9	12	39	42		173	259			Tidal Ledger page 92		
	Dunbar	1945	12	9.81	8.90		276	0		276	0	4	279	56.006	-2.517	190	0.000	1916	1.344	39	9	0	22	23		173	260	01-Jul-1945	365	IH		
	Dunbar	1972	3	8.54	7.64		274	0		274	-60	-7	207	56.006	-2.517	190	0.000	1916	1.344	75	9	0	33	34		173	261	31-Oct-1972	21-Jan-1973	NOC Archives		
	Leith	1891	0.5	8.00	7.30	213		-31	91	274	60	4	337	55.983	-3.183	802	1.037	1916	1.625	-41	9	12	39	42		173	262	01-May-1891	16-May-1891	USCGS TT 1914		
	Leith	1908	12	10.02	9.25	235		-31	91	295	0	13	308	55.983	-3.183	802	1.037	1916	1.625	-13	9	12	22	26		173	263	01-Feb-1908	01-Feb-1909	IHB 59		
	Leith	1945	1	10.10	9.25	259		0	91	351	43	3	397	55.983	-3.183	802	1.037	1916	1.625	47	9	0	30	31		173	264	07-Mar-1945	29	IHB 754		
	Leith	1955	12	9.89	9.25	195		0	91	287	0	12	299	55.983	-3.183	802	1.037	1916	1.625	63	9	0	22	23		173	265	01-Jan-1955	31-Dec-1955	IHB 913		
	Granton	1845	12	10.05	9.25	244		-31	91	304	0	1	305	55.983	-3.217	802	3.110	1916	1.638	-116	15	12	22	29		173	266	01-Jan-1845	31-Dec-1845	Tidal Ledger page 150		
	Granton	1859	0.5	10.24	9.84		121	0	79	200	3	-19	185	55.983	-3.217	802	3.110	1916	1.638	-93	15	0	37	40		173	267	17-Aug-1859	03-Sep-1859	OS 1859		OS
	Rosyth	1918		9.47	8.75	219		-31	12	201	0	0	201	56.017	-3.450	1074	0.000	1916	1.729	3	9	12	39	42		201	268	1918	1919	ATT		
	Rosyth	1920	1	8.95	8.75	61		0	61	122	46	-17	151	56.017	-3.450	1074	0.000	1916	1.729	7	9	0	28	29		201	269	11-May-1920	08-Jun-1920	IHB 2122		
	Rosyth	1944		9.50	8.75	229		-31	61	259	0	0	259	56.017	-3.450	1074	0.000	1916	1.729	48	9	12	39	42		201	270	1944		Admiralty chart		
	Rosyth	1966	12	9.39	8.33		323			323	0	-8	315	56.017	-3.450	1074	0.000	1916	1.729	86	9	0	22	23		201	271	01-Jul-1966	365	Tidal analysis 47		
	Burntisland	1945	1	10.03	9.25		238	0	61	299	43	3	345	56.050	-3.233	1074	13.962	1916	1.660	48	32	0	30	44		201	272	07-Mar-1945	29	IHB 759		
	Dundee	1835	12	8.22	7.58	195		24	-2	217	0	3	220	56.450	-2.967	1074	56.692	1916	1.614	-131	64	12	22	69		201	273	01-Jan-1835	31-Dec-1835	Tidal Ledger page 92		
	Dundee	1837	12	10.53	9.74	241		24	-2	263	0	11	274	56.450	-2.967	1074	56.692	1916	1.614	-128	64	12	22	69		201	274	01-Jan-1837	31-Dec-1837	Whewell 1839		
	Dundee	1859	0.5	12.27	11.27		304		15	319	-12	-67	240	56.450	-2.967	1074	56.692	1916	1.614	-92	64	0	52	83		201	275	31-Aug-1859	17-Sep-1859	OS 1859		OS
	Dundee	1897	12	10.35	9.74	187		24	-2	209	0	-1	207	56.450	-2.967	1074	56.692	1916	1.614	-31	64	12	22	69		201	276	01-Jan-1897	31-Dec-1897	Thompson 1914		
	Dundee	1898	12	10.45	9.74	215		24	-2	237	0	-6	231	56.450	-2.967	1074	56.692	1916	1.614	-29	64	12	22	69		201	277	01-Jan-1898	31-Dec-1898	Thompson 1914		
	Dundee	1899	12	10.48	9.74	225		24	-2	247	0	4	251	56.450	-2.967	1074	56.692	1916	1.614	-27	64	12	22	69		201	278	01-Jan-1899	31-Dec-1899	Thompson 1914		
	Dundee	1900	12	10.39	9.74	197		24	-2	219	0	-1	217	56.450	-2.967	1074	56.692	1916	1.614	-26	64	12	22	69		201	279	01-Jan-1900	31-Dec-1900	Thompson 1914		
	Dundee	1901	12	10.30	9.74	171		24	-2	193	0	10	202	56.450	-2.967	1074	56.692	1916	1.614	-24	64	12	22	69		201	280	01-Jan-1901	31-Dec-1901	Thompson 1914		
	Dundee	1902	12	10.32	9.74	176		24	-2	198	0	15	213	56.450	-2.967	1074	56.692	1916	1.614	-23	64	12	22	69		201	281	01-Jan-1902	31-Dec-1902	Thompson 1914		
	Dundee	1903	12	10.59	9.74	259		24	-2	281	0	-10	271	56.450	-2.967	1074	56.692	1916	1.614	-21	64	12	22	69		201	282	01-Jan-1903	31-Dec-1903	Thompson 1914		
	Dundee	1904	12	10.39	9.74	198		24	-2	220	0	1	221	56.450	-2.967	1074	56.692	1916	1.614	-19	64	12	22	69		201	283	01-Jan-1904	31-Dec-1904	Thompson 1914		
	Dundee	1905	12	10.33	9.74	181		24	-2	203	0	7	210	56.450	-2.967	1074	56.692	1916	1.614	-18	64	12	22	69		201	284	01-Jan-1905	31-Dec-1905	Thompson 1914		
	Dundee	1906	12	10.29	9.74	168		24	-2	190	0	0	190	56.450	-2.967	1074	56.692	1916	1.614	-16	64	12	22	69		201	285	01-Jan-1906	31-Dec-1906	Thompson 1914		
	Dundee	1907	12	10.32	9.74	177		24	-2	199	0	7	206	56.450	-2.967	1074	56.692	1916	1.614	-15	64	12	22	69		201	286	01-Jan-1907	31-Dec-1907	Thompson 1914		
	Dundee	1908	12	10.27	9.74	162		24	-2	184	0	14	198	56.450	-2.967	1074	56.692	1916	1.614	-13	64	12	22	69		201	287	01-Jan-1908	31-Dec-1908	Thompson 1914		
	Dundee	1909	12	10.36	9.74	189		24	-2	211	0	8	219	56.450	-2.967	1074	56.692	1916	1.614	-11	64	12	22	69		201	288	01-Jan-1909	31-Dec-1909	Thompson 1914		
	Dundee	1910	12	10.37	9.74	193		24	-2	215	0	-1	214	56.450	-2.967	1074	56.692	1916	1.614	-10	64	12	22	69		201	289	01-Jan-1910	31-Dec-1910	Thompson 1914		
	Dundee	1911	12	10.40	9.74	202		24	-2	224	0	10	234	56.450	-2.967	1074	56.692	1916	1.614	-8	64	12	22	69		201	290	01-Jan-1911	31-Dec-1911	Thompson 1914		
	Dundee	1912	12	10.53	9.74	242		24	-2	264	0	-2	261	56.450	-2.967	1074	56.692	1916	1.614	-6	64	12	22	69		201	291	01-Jan-1912	31-Dec-1912	Thompson 1914		
	Arbroath	1939	1	7.97	7.20		235	0	-85	150	36	22	208	56.557	-2.583	1074	80.425	1916	1.456	33	76	0	30	82		201	292	06-Jun-1939	30	IHB 2225		
																											293					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/y	mm	No.	date	date or days			
P	Aberdeen	1859	0.5	12.62	11.48		346		-93	253	-13	-58	182	57.150	-2.067	361	0.924	1944	1.217	-103	9	0	47	48	1.998	115	294	29-Aug-1859	13-Sep-1859	OS 1859		OS
ABERDEEN	Aberdeen	1964	12	9.78	8.96		250	0		250	-1	9	258	57.150	-2.067	361	0.924	1944	1.217	24	9	0	29	30		115	295	01-Jan-1963	31-Dec-1963			
																											296					
Q	Banff	1859	0.5	10.61	9.59		311	0	-91	220	-22	-40	158	57.669	-2.523	1281	26.375	1944	1.327	-113	44	0	40	59	2.291	155	297	03-Sep-1859	19-Sep-1859	OS 1859		OS
WICK	Portsoy	1859	0.5	16.38	14.85		466	0	-73	393	-59	-63	271	57.686	-2.690	1281	16.585	1944	1.383	-118	35	0	40	53		155	298	23-Sep-1859	08-Oct-1859	OS 1859		OS
	Buckie	1907		6.63	5.42	367		-70	43	340	0	0	340	57.667	-2.967	1281	0.000	1944	1.480	-55	9	12	40	42		155	299	1907		Admiralty chart 1462		
	Buckie	2017	9	334	0		334	0	0	334	2	-20	316	57.667	-2.967	1281	0.000	1944	1.480	108	9	0	22	23		155	300	01-Apr-2017	31-Dec-2017	SEPA and EA (river levels)		
	Buckie	2018	12	322	0		322	0	0	322	-1	-11	310	57.667	-2.967	1281	0.000	1944	1.480	110	9	0	20	21		155	301	01-Jan-2018	31-Dec-2018	SEPA and EA (river levels)		
	Inverness	1837	24?	7.89	7.67	67		-70	96	93	0	0	93	57.478	-4.225	944	23.095	1944	1.799	-193	41	12	40	58		143	302			Tidal Ledger page 208		
	Inverness	1947	0.5	8.66	7.67		302		96	398	-19	3	382	57.478	-4.225	944	23.095	1944	1.799	5	41	0	40	57		143	303	09-Sep-1947	15	IHB 2200		
	Inverness	2017	9	298	0		298	0	0	298	2	-14	286	57.478	-4.225	944	23.095	1944	1.799	131	41	0	22	46		143	304	01-Apr-2017	31-Dec-2017	SEPA and EA (river levels)		
	Inverness	2018	12	289	0		289	0	0	289	-1	-16	273	57.478	-4.225	944	23.095	1944	1.799	133	41	0	20	45		143	305	01-Jan-2018	31-Dec-2018	SEPA and EA (river levels)		
	Cromarty	1915	12	8.07	6.75	402		-70	-6	326	0	-30	296	57.684	-4.038	944	7.649	1944	1.693	-49	24	12	20	33		143	306	01-Jan-1915	31-Dec-1915	Tidal Ledger page 58		
	Cromarty	2017	9	289	0		289	0	0	289	2	-14	277	57.684	-4.038	944	7.649	1944	1.693	124	24	0	22	32		143	307	01-Apr-2017	31-Dec-2017	SEPA and EA (river levels)		
	Cromarty	2018	12	265	0		265	0	0	265	-1	-16	249	57.684	-4.038	944	7.649	1944	1.693	125	24	0	20	31		143	308	01-Jan-2018	31-Dec-2018	SEPA and EA (river levels)		
	Invergordon	1916	12	7.83	6.75	329		-70	43	302	0	-60	241	57.686	-4.170	944	0.357	1944	1.703	-48	9	12	20	24		143	309	01-Jan-1916	31-Dec-1916	Tidal Ledger		
	Invergordon	1917	1	7.80	6.75		320		43	363	57	-17	403	57.686	-4.170	944	0.357	1944	1.703	-46	9	0	30	31		143	310	08-Jul-1917	29	IHB 2132		
	Invergordon	1968	12	7.43	6.60		252	0		252	-1	26	277	57.686	-4.170	944	0.357	1944	1.703	41	9	0	20	21		143	311	01-Jul-1968	365	Tidal analysis 27		
	Wick	1849	13	5.54	5.27	83		0		83	5	21	109	58.441	-3.086	1109	0.000	1944	1.117	-106	9	0	20	21		145	312	01-Jun-1849	30-Jun-1850	Tidal Ledger		
	Wick	1850	3	5.60	5.27	100		-30		70	89	6	165	58.441	-3.086	1109	0.000	1944	1.117	-105	9	12	26	30		145	313	01-Apr-1850	30-Jun-1850	IHB 2132		
	Wick	1965	3	6.47	5.60		264			264	-17	58	304	58.441	-3.086	1109	0.000	1944	1.117	23	9	0	23	25		145	314	21-Dec-1964	31-Mar-1965	Tidal analysis 61		
	Thurso	1843	6	7.75	6.59	354		27	-213	168	0	0	168	58.617	-3.550	1109	33.260	1944	1.049	-106	49	12	21	55		145	315			OS 1862		
	Thurso	1840	72?	7.98	6.59	424		27	-213	238	0	0	238	58.617	-3.550	1109	33.260	1944	1.049	-109	49	12	40	64		145	316			Tidal Ledger page 414		
	Scrabster	1967	2	8.92	8.07	259		0		259	97	-6	350	58.617	-3.550	1109	33.260	1944	1.049	24	49	0	27	56		145	317	11-Apr-1967	31-May-1967	Tidal analysis 169		
																											318					
R	Rispond	1838	0.5	7.16	6.56		182	27	-160	49	64	28	142	58.548	-4.658	1775	24.948	1944	1.079	-114	42	12	29	53	3.195	193	319	15-Jul-1838	17	Ross Clark 1858		
KINLOCHBERVIE	Rispond	1859	0.5	9.44	7.63		550		-160	390	-107	-11	272	58.548	-4.658	1775	24.948	1944	1.079	-92	42	0	33	54		193	320	25-Oct-1859	17-Nov-1859	OS 1859		OS
	Rispond	1903	0.5	7.25	6.50	229		27	-160	96	0	0	96	58.548	-4.658	1775	24.948	1944	1.079	-44	42	12	53	69		193	321	1903		Admiralty Chart 2076 1905 rev.		
	Kinlochbervie	1908	0.5	6.75	5.50	381		27	-125	283	0	0	283	58.457	-5.050	1775	0.000	1944	1.105	-40	9	12	53	55		193	322			Admiralty Chart 2503 1911 rev.		
	Badcall	1933	0.5	7.85	6.40	442		27	-93	376	0	0	376	58.326	-5.141	1775	15.420	1944	1.203	-13	33	12	53	64		193	323			Admiralty Chart 2502 1945 rev.		
																											324					
S	Stornoway	1928	12	7.52	7.30		67	0		67	-2	-2	63	58.208	-6.389	314	0.000	1916	0.940	11	9	0	27	28	2.788	12	325	01-Apr-1928	365	IHB 68		
STORNOWAY	Stornoway	1959	12	7.77	7.30		144	0		144	-2	-13	129	58.208	-6.389	314	0.000	1916	0.940	40	9	0	27	28		12	326	01-Jan-1959	31-Dec-1959	IHB 925		
	Stornoway	1851						72		72	0	0	72	58.208	-6.389	314	0.000	1916	0.940	-61	9	12	41	43		12	327			First OS Map date		
																											328					
T	Lochinver	1859	0.5	11.67	10.06		492	0	-120	372	-2	-64	306	58.146	-5.243	1112	28.347	1944	1.333	-113	45	0	38	59	2.931	174	329	31-Aug-1859	15-Sep-1859	OS 1859		OS
ULLAPOOL	Lochinver	1928	1	7.90	6.30	488		0	-120	368	-19	43	391	58.146	-5.243	1112	28.347	1944	1.333	-21	45	0	27	53		174	330	02-Sep-1928	30-Sep-1928	IHB 2001		
	Loch Broom	1908	0.5			178		72	-70	180	0	0	180	57.937	-5.188	1112	4.982	1944	1.498	-54	19	12	45	50		174	331	1908		Datum Ledger I pg 25, Admiralty Chart 2500 1911		
	Ullapool	1849	0.5	7.75	7.20	168		72	-70	170	0	0	170	57.895	-5.161	1112	0.202	1944	1.531	-145	9	12	45	47		174	332			Admiralty chart 2500, 1865		
	Ullapool	1966	12	9.92	9.02		274			274	2	-5	271	57.895	-5.161	1112	0.202	1944	1.531	34	9	0	17	19		174	333	01-Jul-1966	365	Tidal analysis 58		
	Mellon Charles	1954	1	8.45	8.00		137		66	203	104	51	359	57.859	-5.628	1112	28.058	1944	1.460	15	45	0	24	51		174	334	14-May-1954	30	IHB 2238		
	Kyleakin	1940	1	7.50	7.80		-91		399	308	-57	3	253	57.273	-5.729	1112	77.156	1944	1.757	-7	75	0	43	86		174	335	04-Oct-1940	29	IHB 2200		
	Loch Hourn	1938	0.5	9.62	7.80		555		-250	305	-33	-17	255	57.140	-5.734	1112	90.790	1944	1.807	-11	81	0	38	89		174	336	22-Sep-1938	15	IHB 2133		
																											337					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
U	Salen	1935	1	7.69	6.70		302	0		302	61	-47	315	56.712	-5.778	1491	20.079	1944	1.910	-17	38	0	26	46	1.856	190	338	21-Jun-1935	20-Jul-1935	IHB 2135		
TOBERMORY	Tobermory	1943	1	7.47	7.50		-9		290	281	14	28	323	56.623	-6.064	1491	0.000	1944	1.845	-2	9	0	38	39		190	339	24-Feb-1943	29	IHB 2226		
	Tobermory	1971	12	7.76	6.62		347			347	1	16	364	56.623	-6.064	1491	0.000	1944	1.845	50	9	0	20	22		190	340	01-Nov-1970	31-Oct-1971	Tidal analysis 180		
	Oban	1859	0.5	9.16	9.60		-134	0	611	477	-35	-68	375	56.417	-5.483	1491	42.386	1944	1.998	-170	55	0	32	64		190	341	12-Sep-1859	29-Sep-1859	OS 1859		OS
	Oban	1910		6.28	6.99		-216	-23	611	372	0	0	372	56.417	-5.483	1491	42.386	1944	1.998	-68	55	12	38	68		190	342			Tidal Ledger page 318 and IHB 11		
	Oban	1912	2	6.28	6.99		-216	0	611	395	13	-13	394	56.417	-5.483	1491	42.386	1944	1.998	-64	55	0	20	59		190	343	01-Apr-1912	31-May-1913	Tidal Ledger page 318 and IHB 11		
	Oban	1971	12	11.42	10.43		302			302	1	10	313	56.417	-5.483	1491	42.386	1944	1.998	54	55	0	20	59		190	344	07-Sep-1970	07-Sep-1971	Tidal analysis 41		
	Oban	1972	12	11.37	10.43		287			287	1	-4	284	56.417	-5.483	1491	42.386	1944	1.998	56	55	0	20	59		190	345	09-Sep-1971	09-Sep-1972	IHB		
	Oban	2017		3110	2716		394	0	0	394	3	-8	389	56.417	-5.483	1491	42.386	1944	1.998	146	55	0	22	59		190	346	01-Apr-2017	31-Dec-2017	SEPA and EA (river levels)		
	Oban	2018		3114	2716		398	0	0	398	1	-33	366	56.417	-5.483	1491	42.386	1944	1.998	148	55	0	20	59		190	347	01-Jan-2018	31-Dec-2018	SEPA and EA (river levels)		
	Crinan	1849	4	9.96	9.70		79	0	290	369	46	16	431	56.083	-5.555	1491	67.756	1944	1.970	-187	70	0	21	73		190	348	15-May-1849	15-Sep-1849	OS 1861		
	Crinan	1850	5	9.96	9.70		79	0	290	369	15	56	439	56.083	-5.555	1491	67.756	1944	1.970	-185	70	0	22	73		190	349	15-Jun-1850	15-Oct-1850	OS 1861		
	Carsaig Bay	1937	1	2.99	3.40		-125		293	168	68	3	239	56.031	-5.639	1491	70.891	1944	1.948	-14	72	0	24	76		190	350	16-Jun-1937	29	Tidal analysis 86		
	Ardrishaig	1847	1	4.85	4.53		96		312	409	0	0	409	56.013	-5.445	1491	77.878	1944	1.971	-191	75	0	38	84		190	351	1847		Tidal Ledger page 3		
	Ardrishaig	1849	1	7.88	7.53		104		312	416	69	32	517	56.013	-5.445	1491	77.878	1944	1.971	-187	75	0	24	79		190	352	01-Jun-1849	30-Jun-1849	OS 1861		
	Ardrishaig	1850	1	7.88	7.53		104		312	416	69	15	500	56.013	-5.445	1491	77.878	1944	1.971	-185	75	0	24	79		190	353	01-Jun-1850	30-Jun-1850	OS 1861		
	Ardrishaig	1850	1	7.88	7.53		104		312	416	-89	-58	269	56.013	-5.445	1491	77.878	1944	1.971	-185	75	0	37	84		190	354	01-Dec-1850	31-Dec-1850	OS 1861		
	Ardrishaig	1851	1	7.88	7.53		104		312	416	69	21	506	56.013	-5.445	1491	77.878	1944	1.971	-183	75	0	24	79		190	355	01-Jun-1851	30-Jun-1851	OS 1861		
	Ardrishaig	1851	1	7.88	7.53		104		312	416	-89	56	383	56.013	-5.445	1491	77.878	1944	1.971	-183	75	0	37	84		190	356	01-Dec-1851	31-Dec-1851	OS 1861		
	Campbeltown	1857	2	6.38	5.98		120		339	459	-51	26	434	55.424	-5.605	1491	136.338	1944	1.775	-154	99	0	19	101		190	357	01-Sep-1857	31-Oct-1857			
																											358					
V	Arrochar	1908	?	7.23	6.58	197		55	138	390	0	0	390	56.200	-4.750	755	50.996	1944	2.024	-73	61	12	52	81	2.773	236	359			Ledger page 3		
MILLPORT	Greenock	1897	12	5.60	6.08	-146		55	390	299	0	-10	289	55.950	-4.767	755	23.907	1944	1.979	-93	42	12	27	51		236	360	01-Jan-1897	31-Dec-1897	ATT 1904		
	Greenock	1912	12	5.34	6.08	-226		55	390	219	0	-5	214	55.950	-4.767	755	23.907	1944	1.979	-63	42	12	27	51		236	361	01-Jan-1912	31-Dec-1912	Ledger page 151		
	Greenock	1913	12	5.34	6.08	-226		55	390	219	0	-16	203	55.950	-4.767	755	23.907	1944	1.979	-61	42	12	27	51		236	362	01-Jan-1913	31-Dec-1913	Ledger page 151		
	Gourock	1948	12	6.10	5.79		94	0	265	360	0	-24	336	55.950	-4.767	755	23.907	1944	1.979	8	42	0	27	49		236	363	01-Jan-1948	31-Dec-1948	IHB 760		
	Cloch Lights	1837	0.5	5.74	6.19	-138		55	391	308	87	-63	332	55.942	-4.880	755	21.377	1944	1.981	-212	39	12	48	63		236	364	26-Apr-1837	13-May-1837	Kyle, App C, 2nd report Comm. 1847		
	Millport	1970	12	6.50	5.41		333			333	0	6	338	55.750	-4.906	755	0.000	1944	1.925	50	9	0	27	28		236	365	01-Jan-1970	31-Dec-1970	Tidal analysis 200		
	Ardrossan	1859	0.5	9.48	9.17		94	0	298	392	-32	-67	294	55.633	-4.817	755	14.118	1944	1.879	-160	32	0	44	55		236	366	12-Sep-1859	29-Sep-1859	OS 1859		OS
	Troon	1909	12	4.42	4.90	-146		55	259	168	0	0	168	55.546	-4.680	755	26.737	1944	1.833	-64	44	12	27	53		236	367	1909		Ledger page 412		
	Ayr	1859	0.5	11.02	10.69		100	0	317	417	16	-14	419	55.467	-4.650	755	35.361	1944	1.793	-152	51	0	44	67		236	368	17-Aug-1859	05-Sep-1859	OS 1859		OS
																											369					
W	Stranraer	1898		4.56	4.70	-42			246	204	0	0	204	54.909	-5.025	1215	9.594	1944	1.502	-69	26	0	45	52	2.128	192	370			HO Chart 1403		
PORTPATRICK	Stranraer	1944		4.55	4.70	-46			246	200	0	0	200	54.909	-5.025	1215	9.594	1944	1.502	0	26	0	45	52		192	371			HO Chart 1404		
	Stranraer	2018	4	2041	1566		475	0	0	475	-72	-8	395	54.909	-5.025	1215	9.594	1944	1.502	111	26	0	28	38		192	372	02-Sep-2018	31-Dec-2018	SEPA and EA (river levels)		
	Portpatrick	1815	1	6.63	6.39	70			200	270	0	0	270	54.843	-5.120	1215	0.000	1944	1.465	-189	9	0	45	45		192	373			Rennie, 2nd Report Comm.		
	Portpatrick	1859	0.5	11.24	10.44		242	0	200	442	-66	-9	366	54.843	-5.120	1215	0.000	1944	1.465	-124	9	0	54	54		192	374	03-Oct-1859	17-Oct-1859	OS 1859		OS
	Portpatrick	1968	12	6.84	6.00		255	0		255	-1	14	268	54.843	-5.120	1215	0.000	1944	1.465	35	9	0	21	23		192	375	23-Nov-1968	365	Tidal analysis 43		
																											376					
X	Silloth	1860	0.5	15.18	15.82		-193	0	214	21	-2	37	56	54.867	-3.400	1794	26.299	1916	1.208	-68	44	0	48	65	2.887	137	377	30-Jan-1860	22-Feb-1860	OS 1859		OS
WORKINGTON	Silloth	1875		13.45	13.50	-15		-104	214	95	0	0	95	54.867	-3.400	1794	26.299	1916	1.208	-50	44	12	48	66		137	378			Tidal Ledger page 379		
	Silloth	1896	0.5				109	0	111	220	0	0	220	54.867	-3.400	1794	26.299	1916	1.208	-24	44	0	67	80		137	379			OS 1896		OS
	Silloth	1937	0.5	13.90	12.90	305		-104		201	0	0	201	54.867	-3.400	1794	26.299	1916	1.208	25	44	12	67	81		137	380			Admiralty Chart 1346		
	Maryport	1875		13.18	13.30	-37		-91	123	-5	0	0	-5	54.717	-3.500	1794	8.509	1916	1.139	-47	25	12	48	55		137	381			Tidal Ledger page 266		
	Maryport	1937	0.5	13.60	12.95	198		-91		107	0	0	107	54.717	-3.500	1794	8.509	1916	1.139	24	25	12	67	73		137	382			Admiralty Chart 1346		
	Workington	1937	0.5	13.93	13.10		253	0		253	59	15	327	54.651	-3.567	1794	0.000	1916	1.113	23	9	0	55	56		137	383	15-Jun-1937	15	IHB 2134		
	Workington	1972	1				233			233	-80	76	229	54.651	-3.567	1794	0.000	1916	1.113	62	9	0	34	35		137	384	07-Oct-1972	04-Nov-1972	Tidal analysis 189		
	Workington	1975	12				223			223	1	42	266	54.651	-3.567	1794	0.000	1916	1.113	66	9	0	14	16		137	385	06-May-1975	04-May-1976	Tidal analysis 190		
	Whitehaven	1836		14.23	13.20	314		-91	-101	122	0	0	122	54.550	-3.589	1794	11.323	1916	1.053	-84	29	12	48	57		137	386			Tidal Ledger page 446		
																											387					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
Y	Douglas	1865	0.5	0.00	0.00	0				0	0	0	0	54.150	-4.467	435	0.000	1866	0.917	-1	9	0	71	71	1.873	47	388	1865		Original OS datum 1865		
DOUGLAS	Douglas	1928	1	12.41	12.13		85			85	45	-25	106	54.150	-4.467	435	0.000	1866	0.917	57	9	0	39	40		47	389	28-May-1928	25-Jun-1928	Tidal analysis 67		
	Peel	1972	1	2900	2750		150			150	36	-18	169	54.223	-4.696	1793	16.011	1866	0.995	105	34	0	53	63		25	390	02-Jul-1972	30	IHB1338		
	Port St. Mary	1972	1	3010	2910		100			100	82	-22	160	54.076	-4.739	1793	2.141	1866	0.896	95	12	0	59	61		25	391	17-Apr-1972	30	IHB1337		
																											392					
Z	Barrow in Furness	1912	12	15.23	14.31	280		-91	64	253	1	-4	251	54.100	-3.200	936	19.766	1916	0.698	-3	38	12	26	47	1.957	75	393	01-Jan-1912	31-Dec-1912	Tidal Ledger page 24		
HEYSHAM	Barrow in Furness	1974	12	16.27	15.58		209	0		209	6	2	217	54.100	-3.200	936	19.766	1916	0.698	41	38	0	26	46		75	394	14-May-1974	10-Jun-1975	IHB		
	Morecambe	1844	7	14.66	14.31	107		-91	9	25	24	30	80	54.067	-2.883	936	4.562	1916	0.617	-44	18	12	27	35		75	395	01-Apr-1844	31-Oct-1844	Tidal Ledger page 266		
	Heysham	1942	1	14.74	14.31	131		0		131	60	18	210	54.032	-2.920	936	0.000	1916	0.606	16	9	0	33	34		75	396	13-Jun-1942	30	IHB 2200		
	Heysham	1964	12	30.11	29.34		233	0		233	1	14	249	54.032	-2.920	936	0.000	1916	0.606	29	9	0	26	27		75	397	01-Jul-1964	365	IHB		
	Fleetwood	1842	11	14.85	14.31	165		-91		74	6	40	119	53.933	-3.000	936	12.131	1916	0.570	-42	30	12	26	41		75	398	01-Feb-1842	31-Dec-1842	Tidal Ledger page 130		
	Fleetwood	1850	9	14.85	14.31	165		-91		74	28	24	125	53.933	-3.000	936	12.131	1916	0.570	-38	30	12	28	42		75	399	01-Feb-1850	31-Oct-1850	Tidal Ledger page 130		
	Fleetwood	1841	3	13.42	12.76	201		-91		110	0	0	110	53.933	-3.000	936	12.131	1916	0.570	-43	30	12	34	47		75	400			OS 1859 quotes OS 1841 value		OS
	Fleetwood	1896	0.5				225	-91		134	0	0	134	53.933	-3.000	936	12.131	1916	0.570	-11	30	12	67	74		75	401			OS 1896		OS
																											402					
AA	Liverpool 2	1977	1	8139	7930		209	0		209	45	28	282	53.450	-3.018	1774	0.000	1916	0.342	21	9	0	57	58	1.682	61	403	08-Jul-1977	29	Tidal analysis 191		
LIVERPOOL	Liverpool	1816	1	4.75	4.67	24		-65	64	23	0	0	23	53.405	-2.995	15	0.647	1916	0.321	-32	9	12	81	82		58	404			Webster 1848		
	Liverpool	1819	1	4.75	4.67	24		-65	64	23	0	0	23	53.405	-2.995	15	0.647	1916	0.321	-31	9	12	81	82		58	405			Webster 1848		
	Liverpool	1820	1	4.75	4.67	24		-65	64	23	0	0	23	53.405	-2.995	15	0.647	1916	0.321	-31	9	12	81	82		58	406			Webster 1848		
	Liverpool	1821	1	4.75	4.67	24		-65	64	23	0	0	23	53.405	-2.995	15	0.647	1916	0.321	-30	9	12	81	82		58	407			Webster 1848, Beardmore 1852		
	Liverpool	1844	0.5	4.81	4.67	43		-65	64	42	52	-19	74	53.405	-2.995	15	0.647	1916	0.321	-23	9	12	103	104		58	408	07-Mar-1844	16-Mar-1844	OS 1896 Original ODL		
	Liverpool	1854	12	4.94	4.67	82		-65	64	81	2	15	98	53.405	-2.995	15	0.647	1916	0.321	-20	9	12	45	47		58	409	01-Jan-1854	31-Dec-1854	Parks, Schoolbred		
	Liverpool	1855	12	4.90	4.67	69		-65	64	69	2	21	91	53.405	-2.995	15	0.647	1916	0.321	-20	9	12	45	47		58	410	01-Jan-1855	31-Dec-1855	Parks, Schoolbred		
	Liverpool	1856	12	5.02	4.67	108		-65	64	107	2	26	135	53.405	-2.995	15	0.647	1916	0.321	-19	9	12	45	47		58	411	01-Jan-1856	31-Dec-1856	Parks, Schoolbred		
	Liverpool	1857	12	4.99	4.67	99		-65	64	98	2	16	115	53.405	-2.995	15	0.647	1916	0.321	-19	9	12	45	47		58	412	01-Jan-1857	31-Dec-1857	Parks, Schoolbred		
	Liverpool	1860	12	5.01	4.67	103		-65	64	102	2	1	105	53.405	-2.995	15	0.647	1916	0.321	-18	9	12	45	47		58	413	01-Jan-1860	31-Dec-1860	Parks, Schoolbred		
	Liverpool	1861	12	5.10	4.67	131		-65	64	130	2	-9	124	53.405	-2.995	15	0.647	1916	0.321	-18	9	12	45	47		58	414	01-Jan-1861	31-Dec-1861	Parks, Schoolbred		
	Liverpool	1862	12	5.11	4.67	135		-65	64	134	2	-8	128	53.405	-2.995	15	0.647	1916	0.321	-17	9	12	45	47		58	415	01-Jan-1862	31-Dec-1862	Parks, Schoolbred		
	Liverpool	1868	12	5.65	4.67	300		-65	64	299	2	-16	285	53.405	-2.995	15	0.647	1916	0.321	-15	9	12	45	47		58	416	01-Jan-1868	31-Dec-1868	Parks, Schoolbred	0	
	Liverpool	1930	12	5.04	4.54		152	0		152	2	-25	129	53.405	-2.995	15	0.647	1916	0.321	4	9	0	45	46		58	417	01-Jul-1930	365	Tidal analysis 30		
	Liverpool	1964	12	5.09	4.54		167	0		167	2	18	186	53.405	-2.995	15	0.647	1916	0.321	15	9	0	45	46		58	418	27-Jun-1964	365	Tidal analysis 31		
	Birkenhead	1859	0.5	17.196	16.08		339	0	-27	312	-93	-63	157	53.400	-3.017	765	0.000	1916	0.321	-18	9	0	98	98		53	419	27-Oct-1859	14-Nov-1859	OS 1859		OS
	Birkenhead	1963	12	15.172	14.54		193	0		193	2	-5	190	53.400	-3.017	765	0.000	1916	0.321	15	9	0	45	46		53	420	01-Jul-1963	365	IHB		
	Birkenhead	1964	12	15.049	14.54		155	0		155	2	18	175	53.400	-3.017	765	0.000	1916	0.321	15	9	0	45	46		53	421	27-Jun-1964	365	IHB		
	Hilbre	1887	12	14.25	14.67	-128		63	58	-7	2	34	29	53.383	-3.233	940	1.105	1916	0.339	-10	9	12	45	47		47	422	01-Jan-1887	31-Dec-1887	Tidal Ledger page 174		
	Hilbre	1858	12	14.28	14.67	-120		88	58	26	2	23	51	53.383	-3.233	940	1.105	1916	0.339	-20	9	12	45	47		47	423	01-Jan-1858	31-Dec-1858	BAAS 1876		
	Hilbre	1859	12	14.41	14.67	-78		88	58	68	2	-14	56	53.383	-3.233	940	1.105	1916	0.339	-19	9	12	45	47		47	424	01-Jan-1859	31-Dec-1859	BAAS 1876		
	Hilbre	1860	12	14.45	14.67	-67		88	58	79	7	5	91	53.383	-3.233	940	1.105	1916	0.339	-19	9	12	48	50		47	425	01-Mar-1860	31-Dec-1860	BAAS 1876		
	Hilbre	1861	12	14.48	14.67	-58		88	58	88	2	-9	81	53.383	-3.233	940	1.105	1916	0.339	-19	9	12	45	47		47	426	01-Jan-1861	31-Dec-1861	BAAS 1876		
	Hilbre	1862	12	14.65	14.67	-7		88	58	139	2	-9	132	53.383	-3.233	940	1.105	1916	0.339	-18	9	12	45	47		47	427	01-Jan-1862	31-Dec-1862	BAAS 1876		
	Hilbre	1863	12	14.45	14.67	-68		88	58	78	3	-17	64	53.383	-3.233	940	1.105	1916	0.339	-18	9	12	46	48		47	428	29-Mar-1863	31-Dec-1863	BAAS 1876		
	Hilbre	1864	12	14.38	14.67	-87		88	58	59	-24	3	38	53.383	-3.233	940	1.105	1916	0.339	-18	9	12	48	50		47	429	03-Jun-1864	31-Dec-1864	BAAS 1876		
	Hilbre	1865	12	14.42	14.67	-78		88	58	68	2	3	74	53.383	-3.233	940	1.105	1916	0.339	-17	9	12	45	47		47	430	01-Jan-1865	31-Dec-1865	BAAS 1876		
	Hilbre	1866	12	14.53	14.67	-44		88	58	102	2	-16	89	53.383	-3.233	940	1.105	1916	0.339	-17	9	12	45	47		47	431	01-Jan-1866	31-Dec-1866	BAAS 1876		
	Hilbre	1867	12	14.42	14.67	-77		88	58	69	2	11	82	53.383	-3.233	940	1.105	1916	0.339	-17	9	12	45	47		47	432	01-Jan-1867	31-Dec-1867	BAAS 1876		
	Hilbre	1964	12	15.22	14.54		208	0		208	2	7	217	53.383	-3.233	940	1.105	1916	0.339	16	9	0	45	46		47	433	27-Feb-1964	365	IHB		
	Hilbre	1977	1	26.40	25.92		147	0		147	45	28	220	53.383	-3.233	940	1.105	1916	0.339	21	9	0	57	58		47	434	08-Jul-1977	29	IHB		
																											435					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
AB	Colwyn Bay	1901	1			0.55		50	52	103	80	-39	143	53.293	-3.728	1854	7.769	1916	0.344	-5	24	12	72	77	1.942	-11	436	12-Apr-1901	04-May-1901	S&M&CE 1907		
HOLYHEAD	Llandudno	1972	16				227			227	-13	-16	198	53.332	-3.825	1854	0.000	1916	0.370	21	9	0	44	45		-11	437	12-Jul-1977	03-May-1978	Tidal analysis 202		
	Beaumaris	1892	4	11.04	11.08	-12		32	64	84	0	0	84	53.267	-4.083	5	36.086	1916	0.358	-9	51	12	53	75		-22	438			Tidal Ledger page 25		
	Beaumaris	1973	1				233			233	-54	0	179	53.267	-4.083	5	36.086	1916	0.358	20	51	0	70	87		-22	439	20-Dec-1972	26-Jan-1973	Tidal analysis 207		
	Holyhead	1838	12	10.43	10.45	-6		32	37	63	0	19	83	53.314	-4.620	5	0.000	1916	0.415	-32	9	12	42	45		-22	440	01-Jan-1838	31-Dec-1838	PSMSL		
	Holyhead	1839	12	10.23	10.45	-67		32	37	2	0	4	6	53.314	-4.620	5	0.000	1916	0.415	-32	9	12	42	45		-22	441	01-Jan-1839	31-Dec-1839	PSMSL		
	Holyhead	1846	8	10.44	10.45	-4		32	37	65	-11	0	53	53.314	-4.620	5	0.000	1916	0.415	-29	9	12	43	46		-22	442	01-May-1846	31-Dec-1846	PSMSL		
	Holyhead	1847	12	10.27	10.45	-54		32	37	15	0	0	15	53.314	-4.620	5	0.000	1916	0.415	-29	9	12	42	45		-22	443	01-Jan-1847	31-Dec-1847	PSMSL		
	Holyhead	1859	0.5	13.23	12.77		141		37	178	-50	-85	43	53.314	-4.620	5	0.000	1916	0.415	-24	9	0	114	115		-22	444	31-Dec-1859	23-Jan-1860	OS 1859		OS
	Holyhead	1908	12	8.30	8.58	-85		32	118	65	0	20	85	53.314	-4.620	5	0.000	1916	0.415	-3	9	12	42	45		-22	445	01-Jan-1908	31-Dec-1908	Tidal Ledger page 176		
	Holyhead	1909	12	8.30	8.58	-85		33	118	66	0	11	78	53.314	-4.620	5	0.000	1916	0.415	-3	9	12	42	45		-22	446	01-Jan-1909	31-Dec-1909	Tidal Ledger page 176		
	Caernarvon	1892	3	8.21	8.08	40		32	-3	69	0	0	69	53.150	-4.267	5	29.779	1916	0.314	-8	46	12	56	74		-22	447			Tidal Ledger page 57		
	Caernarvon	1962	1	9.71	8.93		238			238	-12	-46	180	53.150	-4.267	5	29.779	1916	0.314	14	46	0	74	87		-22	448	07-Sep-1962	30	IHB 1074		
	Fort Belan	1892	3	6.92	7.20	-85		32		-53	0	0	-53	53.117	-4.333	5	29.097	1916	0.302	-7	46	12	56	74		-22	449			Tidal Ledger page 25		
	Portdinllaen	1892	3	6.86	7.02	-49		32	-3	-20	0	0	-20	52.950	-4.567	5	40.627	1916	0.239	-6	54	12	56	79		-22	450			Tidal Ledger page 90		
																											451					
AC	Pwllheli	1889	2	7.10	7.20	-30		-60		-90	15	-6	-82	52.887	-4.406	939	104.777	1916	0.206	-6	87	12	24	91	2.419	-3	452	01-Jul-1889	30-Sep-1889	Tidal ledger pg 331		
FISHGUARD	Porthmadog	1889	2	7.28	6.74	165		-60		105	-43	-18	44	52.928	-4.133	939	116.874	1916	0.213	-6	92	12	28	97		-3	453	15-Sep-1889	15-oct-1889	Tidal ledger pg 267		
	Barmouth	1890	1	7.52	7.00	158		-80	12	90	34	-47	77	52.719	-4.045	1771	0.000	1916	0.134	-3	9	12	31	35		-2	454	01-Jun-1890	30-Jun-1890	Tidal Ledger page 26		
	Aberdovey	1890	6	7.16	7.18	-6		-80		-86	10	-4	-80	52.550	-4.050	939	87.161	1916	0.079	-2	79	12	23	84		-3	455	01-May-1890	31-Oct-1890	Tidal Ledger page 3		
	Cardigan	1859	0.5	5.66	4.88		237		-46	191	64	-53	203	52.467	-4.150	939	75.930	1916	0.055	-3	74	0	51	90		-3	456	17-Apr-1859	26-Apr-1859	OS 1859	0	OS
	Cardigan	1896	0.5				424		-46	378	0	0	378	52.467	-4.150	939	75.930	1916	0.055	-1	74	0	65	99		-3	457			OS 1896	0	OS
	Aberystwyth	1972	2				260			260	-27	88	321	52.410	-4.088	939	75.335	1916	0.038	2	74	0	24	78		-3	458	25-Aug-1972	17-Oct-1972	Tidal analysis 206		
	New Quay	1891	3	7.13	6.92	64		-100	21	-15	15	-33	-33	52.217	-4.367	939	47.824	1916	-0.016	0	59	12	24	65		-3	459	01-Jul-1891	30-Sep-1891	Tidal Ledger page 300		
	New Quay	1892	3	7.13	6.92	64		-100	21	-15	14	-11	-11	52.217	-4.367	939	47.824	1916	-0.016	0	59	12	24	65		-3	460	01-Jul-1892	30-Sep-1892	Tidal Ledger page 301		
	Fishguard	1959	2	5.97	5.70		82			82	6	61	149	52.013	-4.984	939	0.000	1916	-0.080	-3	9	0	26	28		-3	461	17-Aug-1959	14-Sep-1959	IHB 2253		
	Fishguard	1963	12	6.73	6.08		197	0		197	0	0	197	52.013	-4.984	939	0.000	1916	-0.080	-4	9	0	23	24		-3	462					
																											463					
AD	St Annes Head	1894	2	11.89	11.82	21		-57	-30	-66	53	-19	-32	51.700	-5.150	1700	6.835	1916	-0.162	4	22	12	48	54	1.531	-93	464	01-Apr-1894	31-May-1894	Tidal Ledger page 380		
MILFORD HAVEN	Milford Dock	1896	0.5				-199		3	-196	0	0	-196	51.709	-5.038	1700	0.927	1916	-0.156	3	9	0	99	99		-93	465			OS 1896		OS
	Milford Dock	1962	12	12.58	12.17		124	0		124	1	4	130	51.709	-5.038	1700	0.927	1916	-0.156	-7	9	0	39	40		-93	466	01-Nov-1961	365	Tidal analysis 36		
	Neyland	1886	12	12.21	11.87	104		-57	-84	-37	1	-19	-56	51.705	-4.943	66	5.111	1916	-0.154	5	19	12	39	45		-71	467	01-Jan-1886	31-Dec-1886	Thompson 1914		
	Neyland	1887	12	11.97	11.87	30		-57	-84	-111	1	33	-77	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	468	01-Jan-1887	31-Dec-1887	Thompson 1914		
	Neyland	1888	12	12.05	11.87	55		-57	-84	-86	1	2	-83	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	469	01-Jan-1888	31-Dec-1888	Thompson 1914		
	Neyland	1889	12	12.00	11.87	40		-57	-84	-101	1	10	-90	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	470	01-Jan-1889	31-Dec-1889	Thompson 1914		
	Neyland	1890	12	12.04	11.87	52		-57	-84	-89	1	-2	-90	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	471	01-Jan-1890	31-Dec-1890	Thompson 1914		
	Neyland	1891	12	12.17	11.87	91		-57	-84	-50	1	-10	-59	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	472	01-Jan-1891	31-Dec-1891	Thompson 1914		
	Neyland	1892	12	12.15	11.87	85		-57	-84	-56	1	0	-55	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	473	01-Jan-1892	31-Dec-1892	Thompson 1914		
	Neyland	1892	12	12.17	11.87	91		-57	-84	-50	0	0	-50	51.705	-4.943	66	5.111	1916	-0.154	4	19	12	39	45		-71	474			Tidal Ledger page 330		
	Pembroke Dock	1832	2	12.46	11.87	181		-57	-50	74	-72	-8	-6	51.697	-4.955	66	4.277	1916	-0.156	13	18	12	58	62		-71	475	05-Nov-1832	31-Dec-1832	Admiralty Survey Royal Society (1833)		
	Pembroke Dock	1833	12	11.93	11.87	21		-57	-50	-86	1	-10	-95	51.697	-4.955	66	4.277	1916	-0.156	13	18	12	39	44		-71	476	01-Jan-1833	31-Dec-1833	Admiralty Survey Royal Society (1833)		
	Pembroke Dock	1834	12	12.19	11.87	98	0	-57	-50	-9	1	32	24	51.697	-4.955	66	4.277	1916	-0.156	13	18	12	39	44		-71	477	01-Jan-1834	31-Dec-1834	Admiralty Survey HMSO (1835)		
	Pembroke Dock	1835	12	12.42	11.87	168		-57	-158	-47	1	18	-28	51.697	-4.955	66	4.277	1916	-0.156	13	18	12	39	44		-71	478	01-Jan-1835	31-Dec-1835	Admiralty Survey OS 1861		
	Pembroke Dock	1836	12	12.42	11.87	168		-57	-158	-47	1	6	-39	51.697	-4.955	66	4.277	1916	-0.156	12	18	12	39	44		-71	479	01-Jan-1836	31-Dec-1836	Admiralty Survey OS 1861		
	Pembroke Dock	1837	12	12.42	11.87	168		-57	-158	-47	1	9	-37	51.697	-4.955	66	4.277	1916	-0.156	12	18	12	39	44		-71	480	01-Jan-1837	31-Dec-1837	Admiralty Survey OS 1861		
	Pembroke Dock	1838	12	12.42	11.87	168		-57	-158	-47	1	5	-41	51.697	-4.955	66	4.277	1916	-0.156	12	18	12	39	44		-71	481	01-Jan-1838	31-Dec-1838	Admiralty Survey OS 1861		
	Pembroke Dock	1892	1	11.97	11.87	30			-30	0	42	-10	33	51.697	-4.955	66	4.277	1916	-0.156	4	18	0	49	52		-71	482	22-May-1892	19-Jun-1892	IHB 2123 and ATT		
																											483					

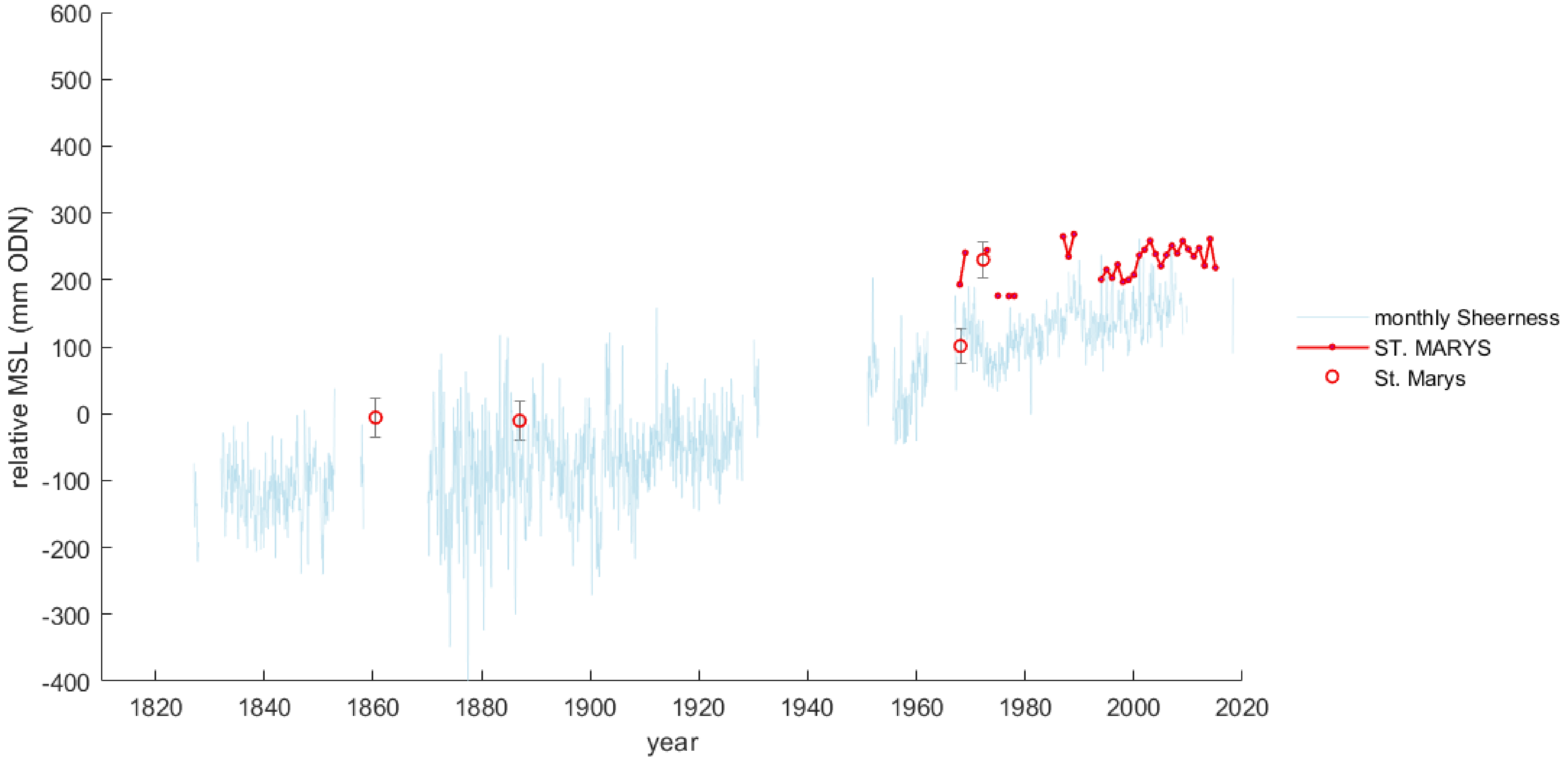
Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																	ODN ref				MTL to		Quad.								
					TGZ				ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
Cluster				MTL or	or CD	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
core	New data			MSL	to OD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
station	location	Year	Months	ft or mm	ft or mm	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/y	mm	No.	date	date or days			
AE	Stackpole Quay	1853	4	12.58	12.17	124		-37		87	-36	19	70	51.625	-4.898	1732	64.040	1916	-0.169	11	68	12	27	74	1.911	-20	484	01-Aug-1853	30-Nov-1853	Tidal Ledger page 381		
MUMBLES	Tenby	1841	1	-21.34	-21.28	-19		-37	-61	-116	0	0	-116	51.667	-4.700	1732	51.165	1916	-0.152	11	61	12	38	73		-20	485	1841		OS 1861 De la Beche		
	Tenby	1886	4	12.87	12.84	9		-37	-61	-88	4	-19	-103	51.667	-4.700	1732	51.165	1916	-0.152	5	61	12	28	68		-20	486	01-Jun-1886	30-Oct-1886	Tidal Ledger page 413		
	Tenby	1931	1	13.32	12.84		146	0	-70	76	-41	113	148	51.667	-4.700	1732	51.165	1916	-0.152	-2	61	0	33	69		-20	487	30-Sep-1931	29	Tidal Ledger page 413 IHB 2083		
	Tenby	1973	1	4490	4500		-10			-10	53	111	154	51.667	-4.700	1732	51.165	1916	-0.152	-9	61	0	45	76		-20	488	27-Mar-1973	30	IHB 1388		
	Burry Port	1862	8	14.31	14.18	40		-37		3	6	-3	6	51.683	-4.250	1732	22.759	1916	-0.130	7	41	12	25	49		-20	489	01-Apr-1862	30-Nov-1862	Tidal Ledger page 27		
	Burry Port	1931	5	14.54	14.18	110		-37		73	0	0	73	51.683	-4.250	1732	22.759	1916	-0.130	-2	41	12	27	50		-20	490	1931		Tidal Ledger page 30		
	Mumbles	1858	4	14.48	14.00	146		-100	-58	-12	-36	8	-40	51.570	-3.975	1732	0.000	1916	-0.137	8	9	12	27	31		-20	491	01-Aug-1858	30-Nov-1858	Tidal Ledger page 381 IHB 2085		
	Mumbles	1859	3	14.97	14.00	296		-100	-58	138	-54	5	88	51.570	-3.975	1732	0.000	1916	-0.137	8	9	12	34	37		-20	492	01-Sep-1858	30-Nov-1858	Tidal Ledger page 381 IHB 2085		
	Mumbles	1861	5	14.48	14.00	146		-100	-58	-12	-21	-32	-65	51.570	-3.975	1732	0.000	1916	-0.137	8	9	12	30	33		-20	493	01-Jul-1861	30-Nov-1861	Tidal Ledger page 381 IHB 2085		
	Mumbles	1883		14.33	14.00	102		-100	-58	-56	0	0	-56	51.570	-3.975	1732	0.000	1916	-0.137	5	9	12	38	41		-20	494			Datum Ledger I pg 379		
	Porthcawl	1860	6	15.17	14.70	143		-100	-70	-27	12	-5	-20	51.467	-3.700	1732	22.254	1916	-0.140	8	40	12	24	48		-20	495	01-May-1860	30-Oct-1860	Tidal Ledger page 381		
	Porthcawl	1949	0.5	14.76	14.30		140		-70	70	52	-13	110	51.467	-3.700	1732	22.254	1916	-0.140	-5	40	0	56	69		-20	496	12-May-1949	15	IHB 2227		
	Porthcawl	1949	0.5	14.76	14.30		140		-69	71	7	27	105	51.467	-3.700	1732	22.254	1916	-0.140	-5	40	0	43	59		-20	497	25-Aug-1949	15	IHB 2227		
	Barry	1861	2	18.30	16.68	494		-72	-226	196	54	63	314	51.383	-3.267	1732	53.295	1916	-0.130	7	62	12	34	72		-20	498	01-Apr-1861	31-May-1861	Tidal Ledger page 27	0	
	Barry	1888	1			480		-72	-226	183	0	0	183	51.383	-3.267	1732	53.295	1916	-0.130	4	62	12	38	74		-20	499			Strahan 1896		
	Barry	1939	1	17.36	16.68		207	0	-226	-18	52	41	75	51.383	-3.267	1732	53.295	1916	-0.130	-3	62	0	39	74		-20	500	12-May-1939	29	IHB 2134		
	Barry	1947	1	17.61	16.68		283	0	-226	58	18	54	130	51.383	-3.267	1732	53.295	1916	-0.130	-4	62	0	31	69		-20	501	14-Aug-1947	29	IHB 761		
	Newport	1947	1	19.80	19.06		226	0		226	18	54	298	51.559	-2.980	1732	68.798	1916	-0.104	-3	71	0	31	77		-20	502	14-Aug-1947	29	IHB 763		
	Cardiff	1847	6	17.51	17.00	156		-72	-193	-109	12	17	-80	51.450	-3.167	1732	57.540	1916	-0.120	8	64	12	25	70		-20	503	01-May-1847	31-Oct-1847	Tidal Ledger page 57		
	Cardiff	1848	6	17.51	17.00	156		-72	-193	-109	-11	3	-116	51.450	-3.167	1732	57.540	1916	-0.120	8	64	12	28	71		-20	504	01-Jun-1848	30-Nov-1848	Tidal Ledger page 57		
	Cardiff	1896					303	0	-193	110	0	0	110	51.450	-3.167	1732	57.540	1916	-0.120	2	64	0	38	75		-20	505					
	Cardiff	1927	0.5	18.80	17.90	274		-72		202	9	-77	135	51.450	-3.167	1732	57.540	1916	-0.120	-1	64	12	43	79		-20	506	23-Aug-1927	15	IHB 762		
																											507					
AF	Avonmouth	1875	0.5	0.98	0.00	299			-104	195	73	47	315	51.508	-2.713	257	0.000	1916	-0.103	4	9	0	98	99	1.418	190	508	07-Apr-1875	29-Apr-1875	BAAS 1876		
AVONMOUTH	Avonmouth	1910	12	21.29	19.83		445		-104	341	0	0	341	51.508	-2.713	257	0.000	1916	-0.103	1	9	0	48	48		190	509	1910		Tidal Ledger page 2		
	Avonmouth	1911	12	21.29	19.83		445		-103	342	0	0	342	51.508	-2.713	257	0.000	1916	-0.103	1	9	0	48	48		190	510	1911		Tidal Ledger page 2		
	Avonmouth	1924	12	21.50	19.83		509		-104	405	0	-34	372	51.508	-2.713	257	0.000	1916	-0.103	-1	9	0	48	48		190	511	01-11-1924	365	IHB 764		
	Avonmouth	1962	12	21.62	20.03		484			484	0	14	498	51.508	-2.713	257	0.000	1916	-0.103	-5	9	0	48	48		190	512	01-Jun-1962	365	IHB		
	Portishead	1869	Hybrid 24	20.81	19.83	299		-30	-134	135	0	0	135	51.500	-2.750	257	2.716	1916	-0.104	5	14	12	82	84		190	513			Tidal Ledger page 331		
	Portishead	1837	1	72.88	71.77	335		-72		263	73	-15	322	51.500	-2.750	257	2.716	1916	-0.104	8	14	12	58	61		190	514	11-Apr-1837	13-May-1837	Bunt 1839 & archive letters (D.P.)		
	Portishead	1838	0.5	72.69	71.77	279		-72		207	20	39	266	51.500	-2.750	257	2.716	1916	-0.104	8	14	12	95	97		190	515	16-Jul-1838	30-Jul-1838	Bunt 1839		
																											516					
AG	Weston super Mar	1848	?	18.30	17.83	143		-72	-58	13	0	0	13	51.350	-2.983	1758	18.606	1916	-0.122	8	37	12	41	56	1.614	54	517	1848		Tidal Ledger page 446		
HINKLEY POINT	Weston super Mar	1859	0.5	19.83	19.71		37	0	-58	-21	47	-53	-27	51.350	-2.983	1758	18.606	1916	-0.122	7	37	0	29	47		54	518	24-May-1859	03-Jun-1859	OS 1859		OS
	Weston super Mar	1896	0.5				186	0	-58	128	0	0	128	51.350	-2.983	1758	18.606	1916	-0.122	2	37	0	58	68		54	519	1896		OS 1896		OS
	Weston super Mar	1953	0.5	19.67	19.20		143	0		143	54	-28	169	51.350	-2.983	1758	18.606	1916	-0.122	-5	37	0	37	52		54	520	21-Apr-1953	15	IHB 2227		
	Wick rocks	1837	1	73.11	72.44		203	-50		153	-81	20	93	51.208	-3.099	1758	2.271	1916	-0.137	11	13	12	26	31		54	521	09-Nov-1837	09-Dec-1837	Bunt 1839		
																											522					
AH	Minehead	1885	5	17.92	17.25	204		-30	-273	-99	23	0	-76	51.217	-3.467	1214	44.981	1916	-0.154	5	57	12	27	64	1.428	-78	523	01-May-1885	30-Sep-1885	Tidal Ledger page 267		
ILFRACOMBE	Ilfracombe	1949	0.5	14.00	12.58		433	0	-390	43	64	-4	102	51.211	-4.112	1214	0.000	1916	-0.192	-6	9	0	62	63		-78	524	19-Apr-1949	15	IHB 2202		
	Ilfracombe	1968	12	16.90	16.09		247	0		247	4	-8	243	51.211	-4.112	1214	0.000	1916	-0.192	-10	9	0	28	29		-78	525	17-Sep-1968	365	Tidal analysis 25		
	Instow	1972	1	2860	2600		260			260	60	-13	307	51.054	-4.177	1214	18.096	1916	-0.212	-12	36	0	44	57		-78	526	27-Apr-1972	30	IHB 1333		
	Appledore	1854		11.21	9.96	381		-50	-165	166	0	0	166	51.050	-4.200	1214	18.932	1916	-0.214	13	37	12	49	62		-78	527	1854	1855	Tidal Ledger page 2	0	
	Appledore	1859	0.5	10.60	9.91		210	0	-165	45	34	42	120	51.050	-4.200	1214	18.932	1916	-0.214	12	37	0	44	57		-78	528	21-Jun-1859	14-Jul-1859	OS 1859	0	OS
	Appledore	1949	1	11.96	9.96		610	0	-165	445	-64	-22	359	51.050	-4.200	1214	18.932	1916	-0.214	-7	37	0	39	54		-78	529	12-Oct-1949	29	IHB 2201	0	
	Boscastle	1972	0.5	1770	1550		220			220	58	-19	259	50.687	-4.693	1214	71.072	1916	-0.279	-16	72	0	41	82		-78	530	02-May-1972	15	IHB 1334		
	Padstow	1835	24?	11.18	11.16	6		-50	-46	-90	0	0	-90	50.550	-4.933	2284	8.541	1916	-0.307	25	25	12	49	56		-174	531	1835		Tidal Ledger page 332		
	Padstow	1972	0.5	2070	1880		190			190	59	0	249	50.550	-4.933	2284	8.541	1916	-0.307	-17	25	0	62	67		-174	532	29-Apr-1972	17	IHB 1335		
																											533					

Table 4		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Summary of all new data by cluster																															
																		ODN ref				MTL to		Quad.								
									ODL or							PSMSL	Dist.	Year			Level.	MSL	Seas.	Total				Start or	End date or	Source	OW	Org
					TGZ	MTL to	MSL to	MTL to	ODN1 to	Level	seas.	met.	MSL			ref	between	Fund.	GIA	GIA	uncert.	uncert.	uncert.	uncert.	SLR	ODN		centre date	duration (days)			
Cluster	New data			MTL or	or CD	OD	ODL	MSL	ODN3	to ODN	adjust	adjust	to ODN	Lat	Long	site	sites	Levelling		offset						offset	row					
core	location			MSL	to OD	mm	mm	mm	mm	mm	mm	mm	mm	(deg)	(deg)	ID	(km)	year	mm/yr	mm	mm	mm	mm	mm	mm/yr	mm	No.	date	date or days			
station		Year	Months	ft or mm	ft or mm																											
AI	St. Helier	1904	1	18.90	18.30	183			-195	-12	31	5	23	49.178	-2.111	1795	0.722	1900	-0.026	0	9	0	58	59	1.880	-163	534	19-Jul-1904	29	IHB 2135		
ST. HELIER	St. Helier	1903	12	18.89	18.30	180			-195	-15	0	0	-15	49.178	-2.111	1795	0.722	1900	-0.026	0	9	0	28	30		-163	535	1903	1904	Tidal ledger pg 382		
	St. Helier	1901		18.50	18.30	61			-195	-134	0	0	-134	49.178	-2.111	1795	0.722	1900	-0.026	0	9	0	53	53		-163	536	1901		Datum Ledger II pg 348		
																											537					
AJ	Lerwick	1933	1	2.87	3.00	-40		0		-40	42	-16	-13	60.154	-1.140	830	0.000	1955	-0.234	5	9	0	25	26	1.101	-156	538	28-Jun-1933	26-Jul-1933	IHB 2122		
LERWICK	Lerwick	1957	12	3.21	3.00	64				64	0	-4	61	60.154	-1.140	830	0.000	1955	-0.234	0	9	0	18	20		-156	539	15-Jul-1957	365	IHB 924		
	Lerwick	1878		3.00	3.00	0		-12		-12	0	0	-12	60.154	-1.140	830	0.000	1955	-0.234	18	9	12	32	36		-156	540	1878	1878	OS MTL datum		
	Quendale Bay	1934	1	2.75	3.00	-76		0	311	235	-50	-69	116	59.893	-1.333	830	30.906	1955	-0.055	1	47	0	23	53		-156	541	12-Sep-1934	10-Oct-1934	IHB 2122		
	Burravoe	1938	1	3.32	3.10	67		0	-119	-52	29	-31	-54	60.499	-1.056	830	38.686	1955	-0.482	8	53	0	25	58		-156	542	26-Jul-1938	29	IHB 2133		IHB

Supplement S5.5: Plots of MSL at all UK cluster sites, all referenced to local ODN

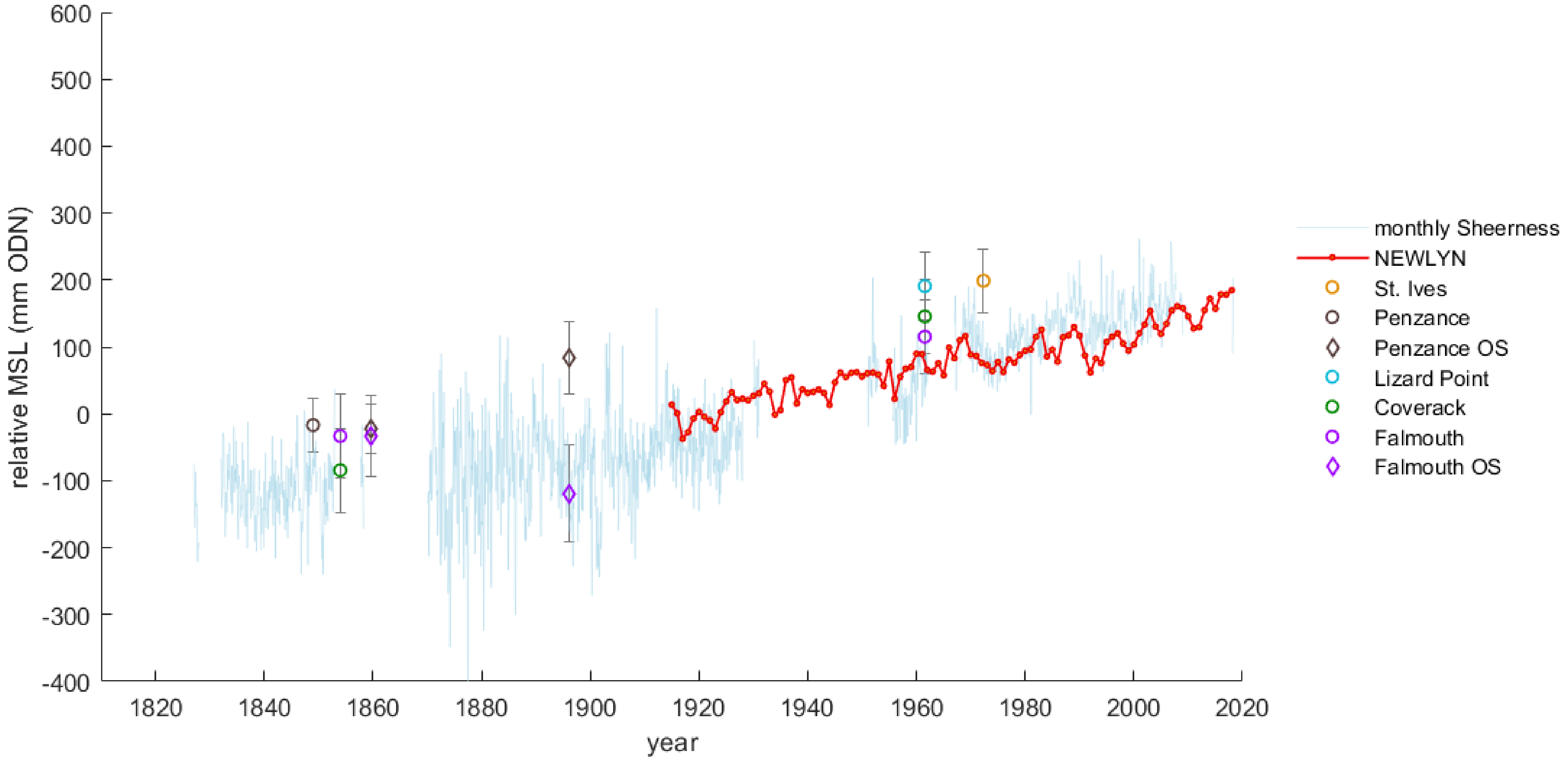
For all plots the filled points (connected by lines if an adjacent annual value exists) represent existing annual MER (extended and adjusted PSMSL) MSL data. All new data values are represented as larger open circles with 1 sigma error bars. The light blue background curve in each plot represents fully adjusted monthly MSL values (light blue) for Sheerness, as this gives a visual reference to compare factors such as: typical month to month variation at any site, the relative ODN offset of the site cluster, and the general similarity in terms of interannual decadal and century scale sea level variation. All data points are adjusted for site specific GIA, meteorological effects, and average seasonal cycle.

St Marys



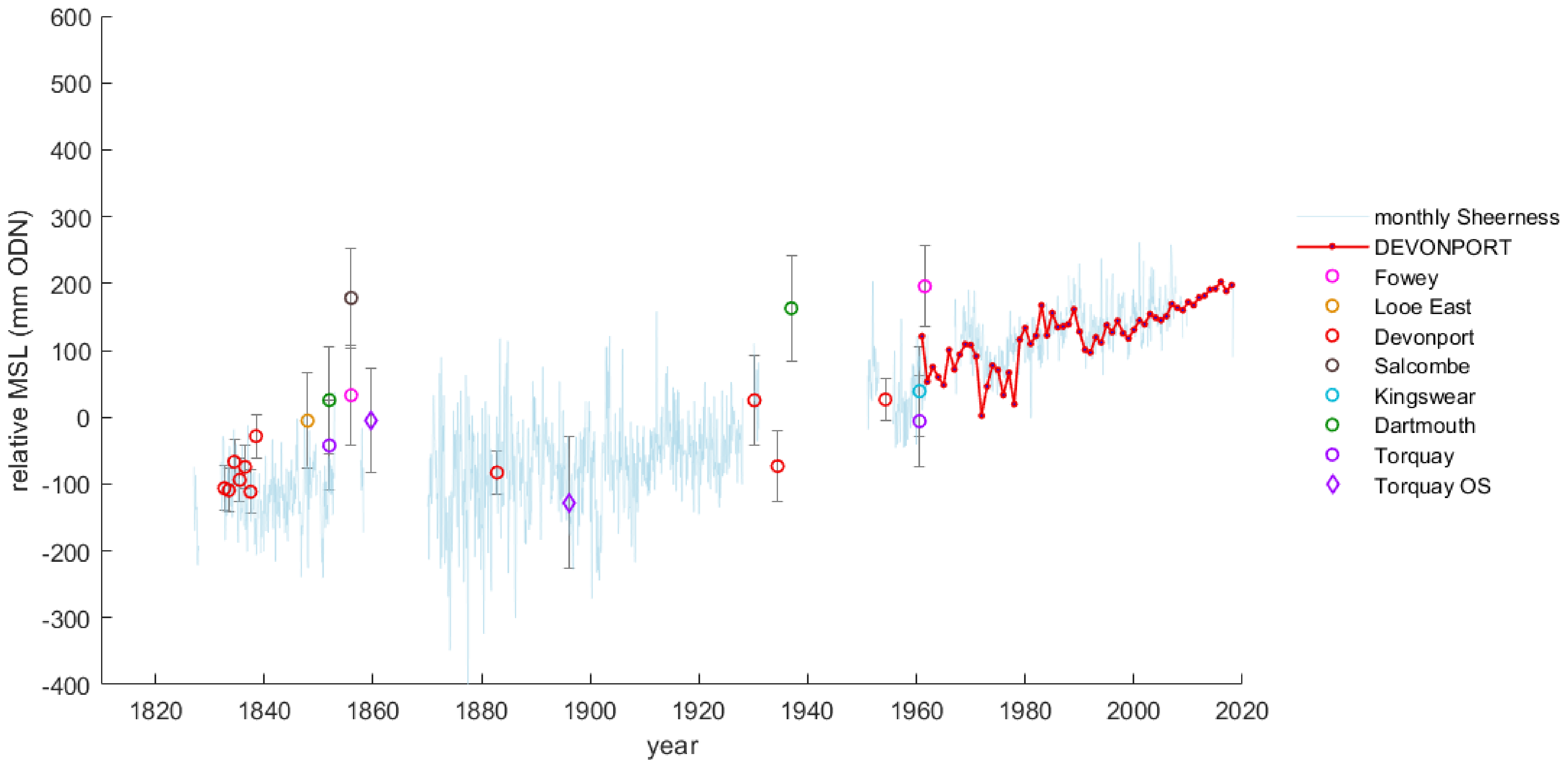
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
ST. MARYS
St. Marys

Newlyn

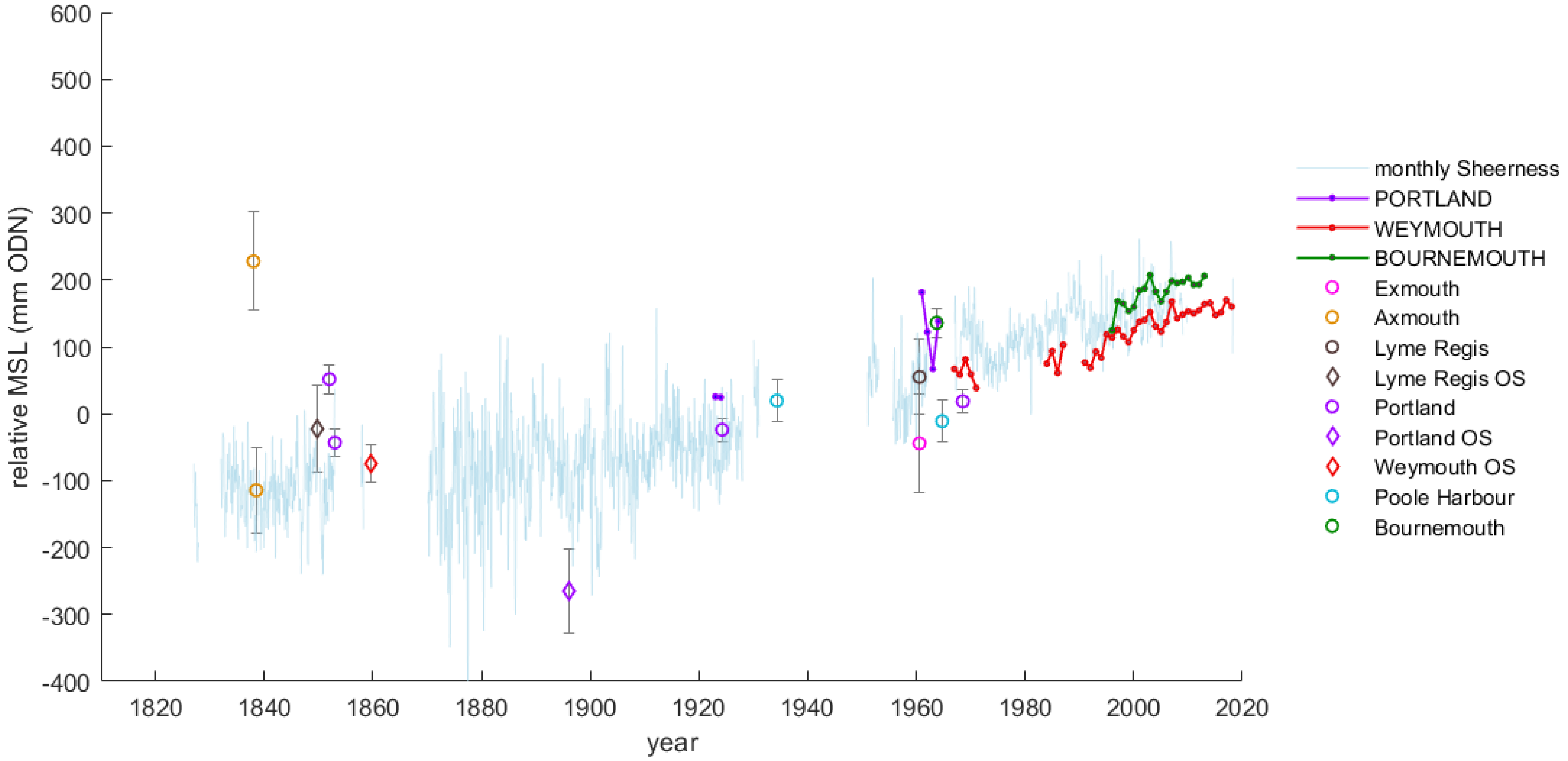


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
NEWLYN
St. Ives
Penzance
Penzance OS
Lizard Point
Coverack
Falmouth
Falmouth OS

Devonport

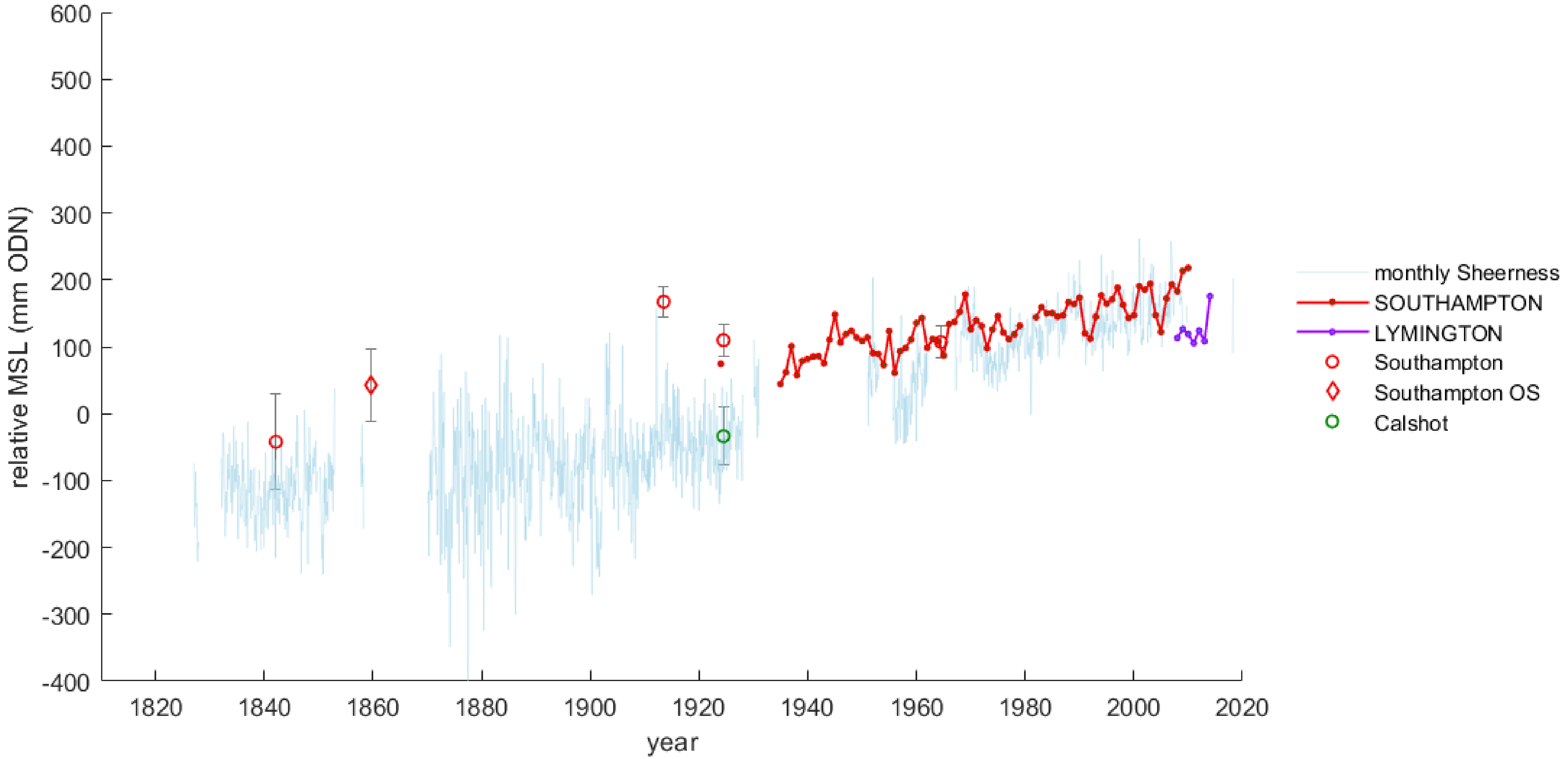

600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
DEVONPORT
Fowey
Looe East
Devonport
Salcombe
Kingswear
Dartmouth
Torquay
Torquay OS

Weymouth

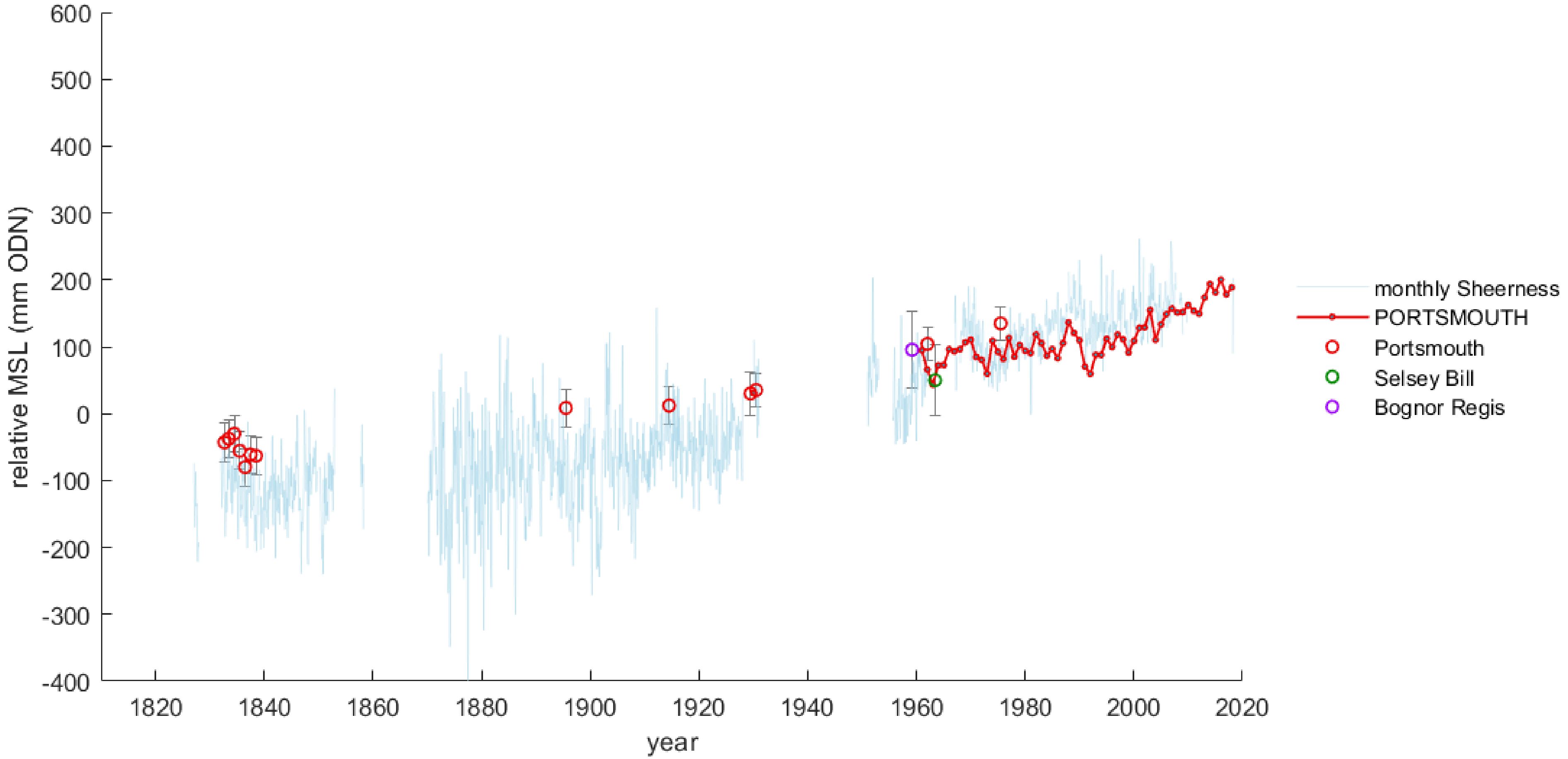


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
PORTLAND
WEYMOUTH
BOURNEMOUTH
Exmouth
Axmouth
Lyme Regis
Lyme Regis OS
Portland
Portland OS
Weymouth OS
Poole Harbour
Bournemouth

Southampton

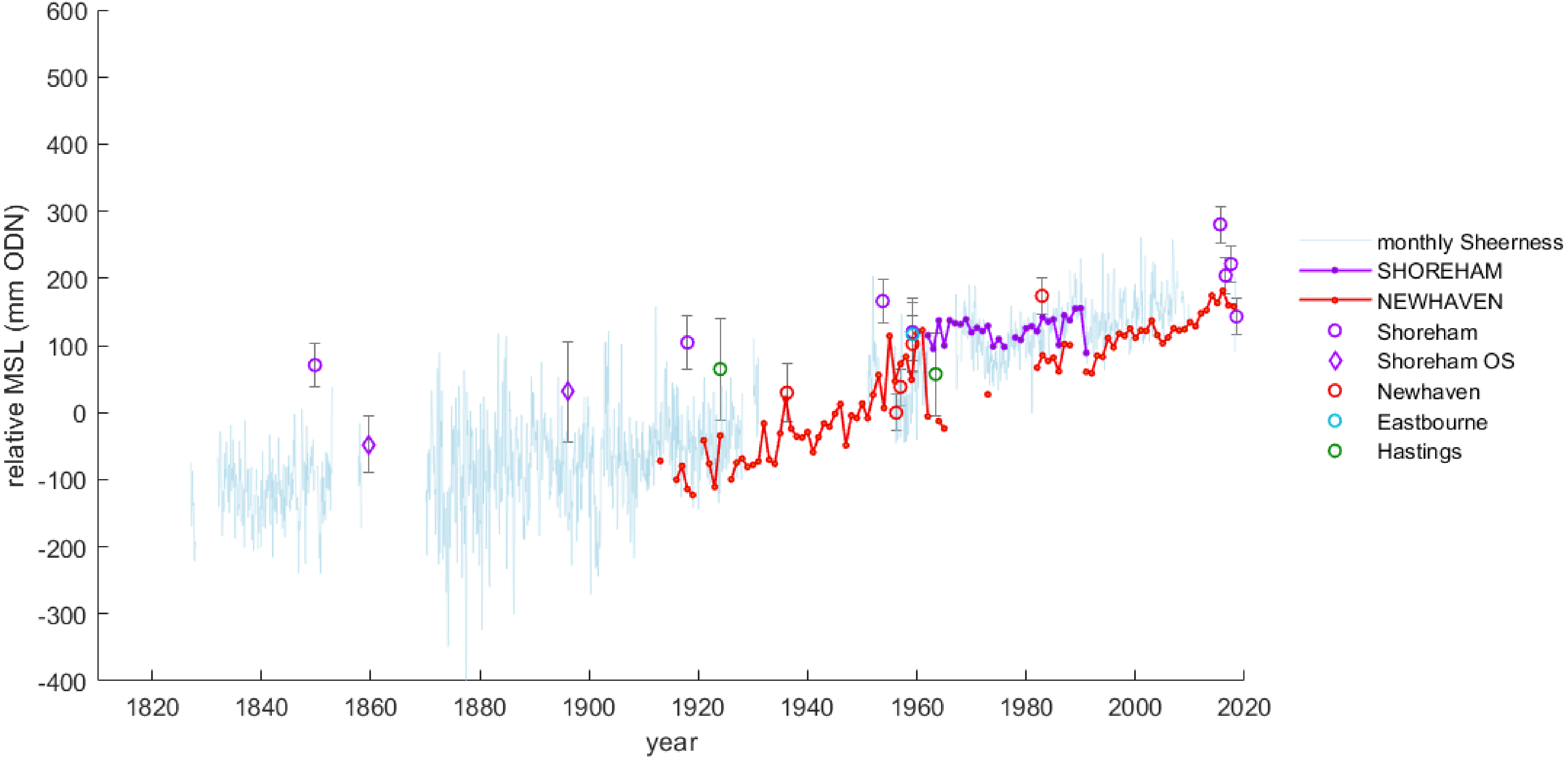


Portsmouth

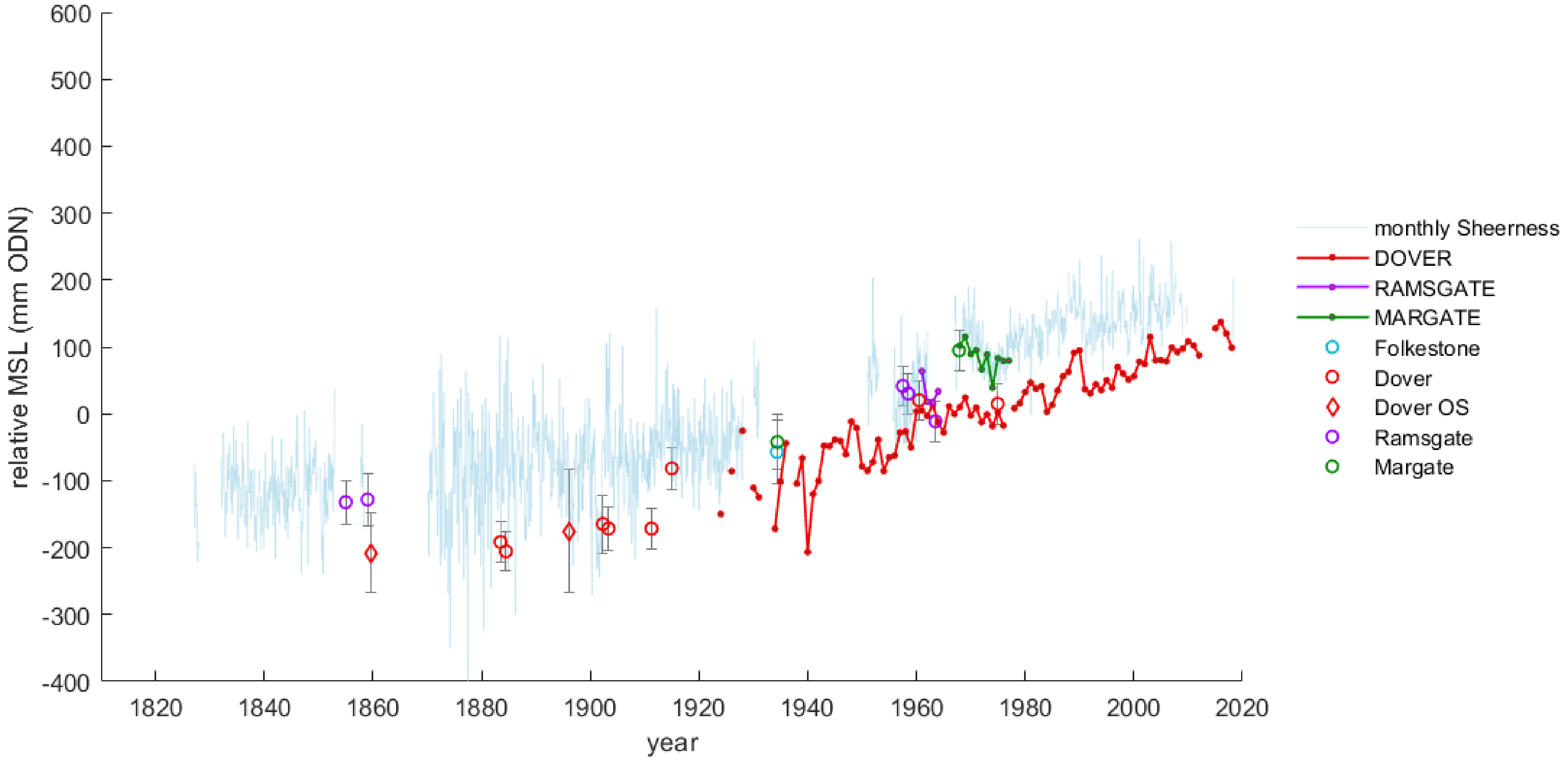


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
PORTSMOUTH
Portsmouth
Selsey Bill
Bognor Regis

Newhaven

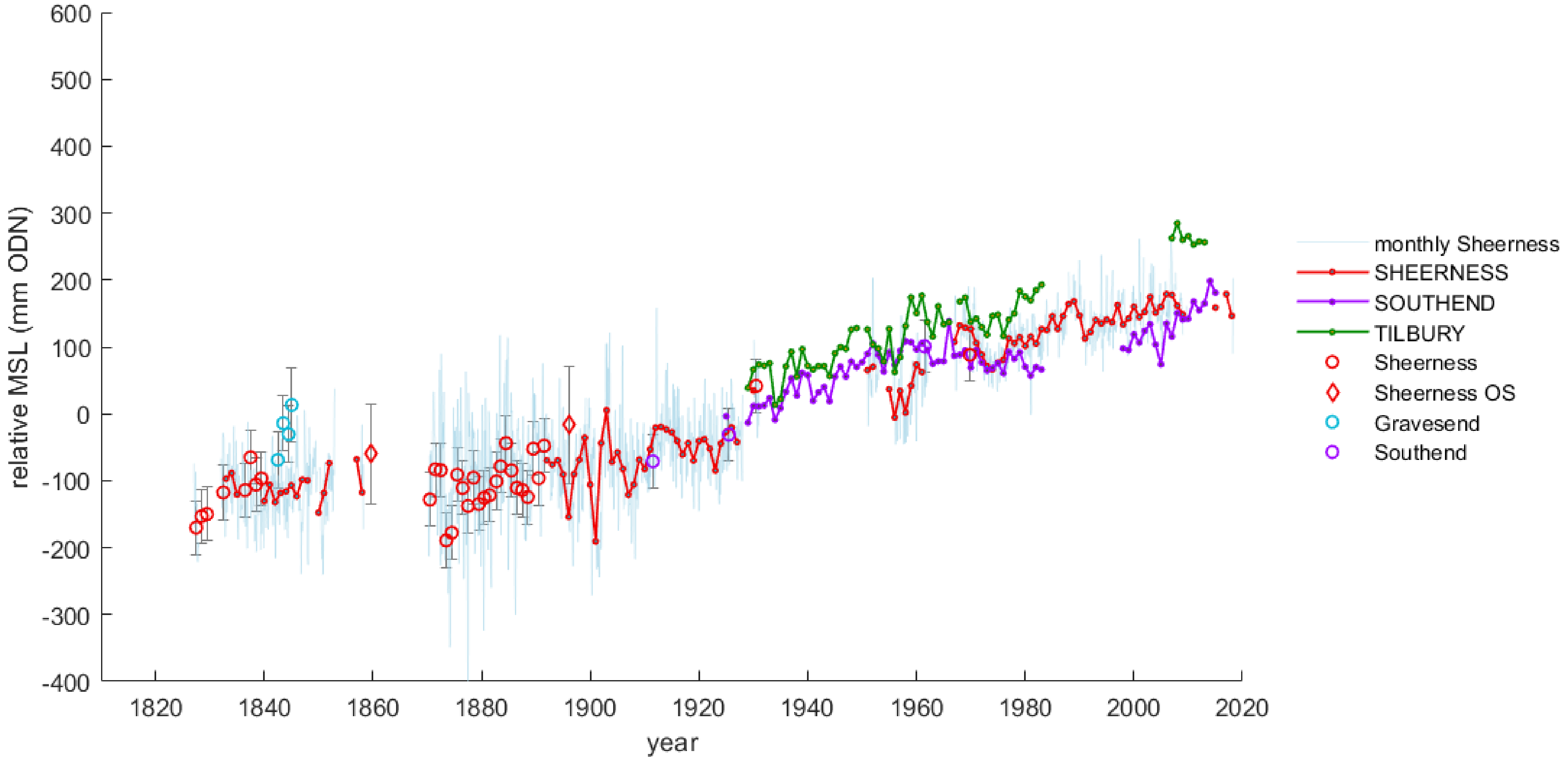

600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
SHOREHAM
NEWHAVEN
Shoreham
Shoreham OS
Newhaven
Eastbourne
Hastings

Dover



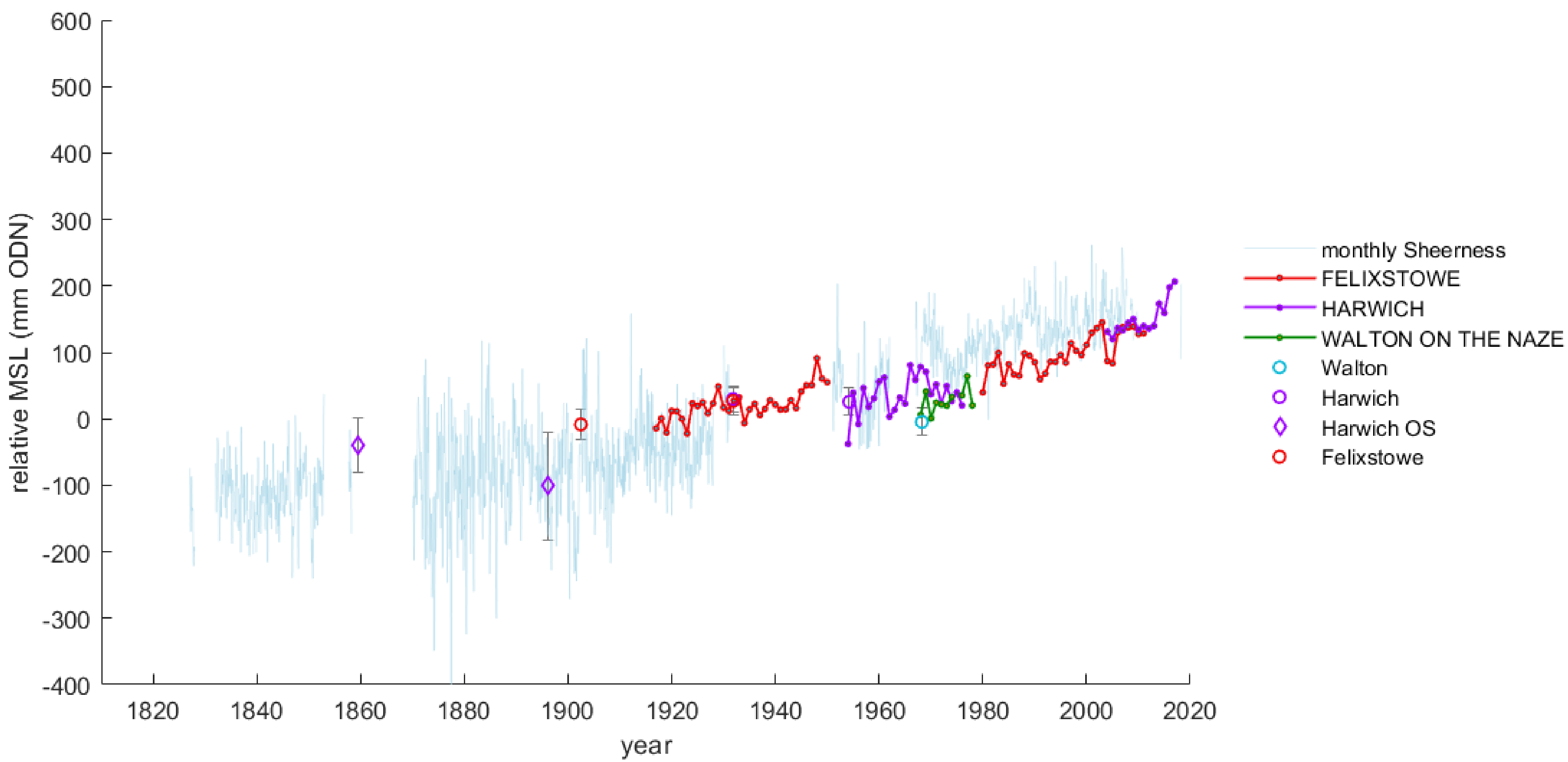
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
DOVER
RAMSGATE
MARGATE
Folkestone
Dover
Dover OS
Ramsgate
Margate

Sheerness



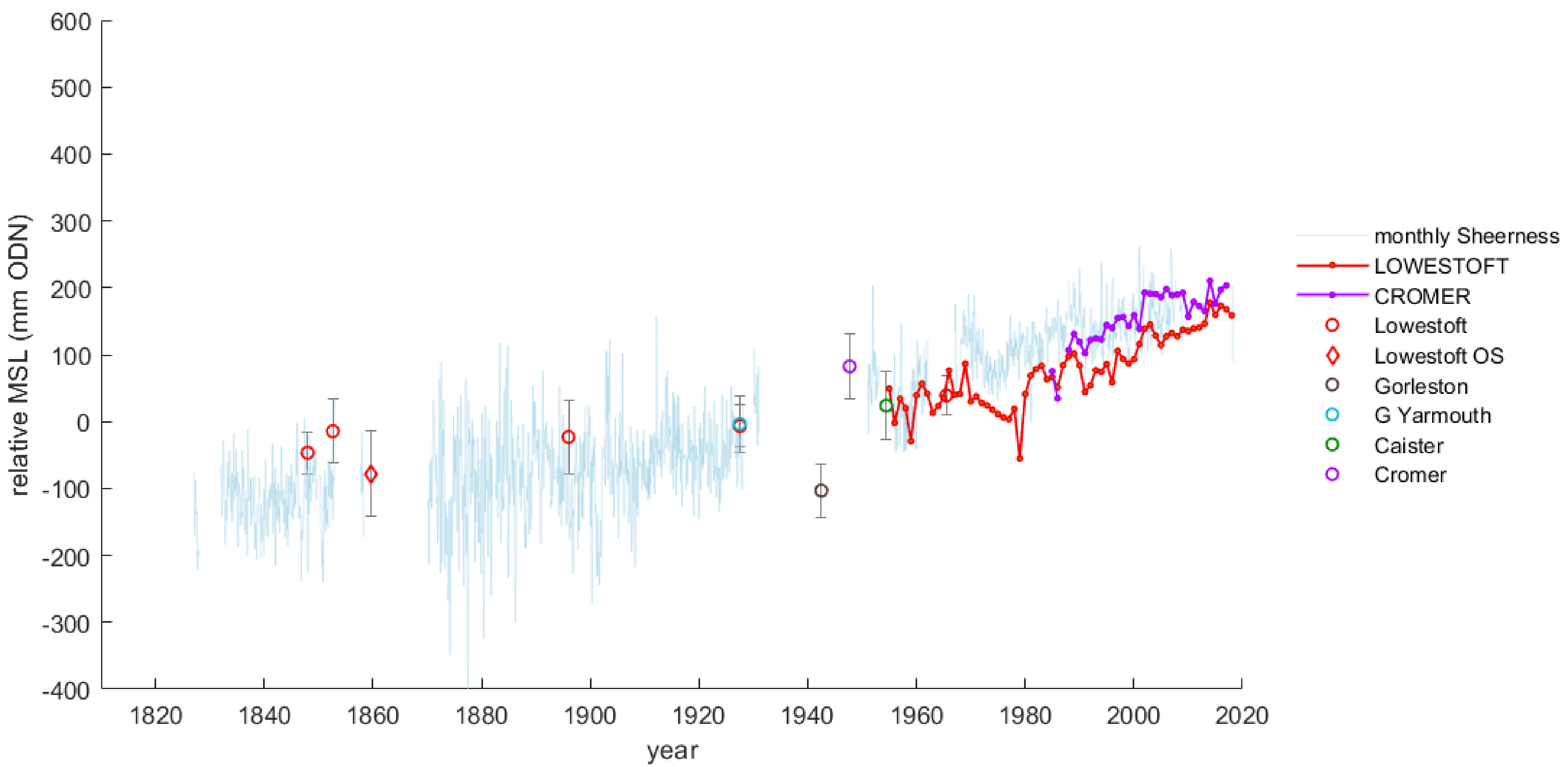
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
SHEERNESS
SOUTHEND
TILBURY
Sheerness
Sheerness OS
Gravesend
Southend

Felixstowe



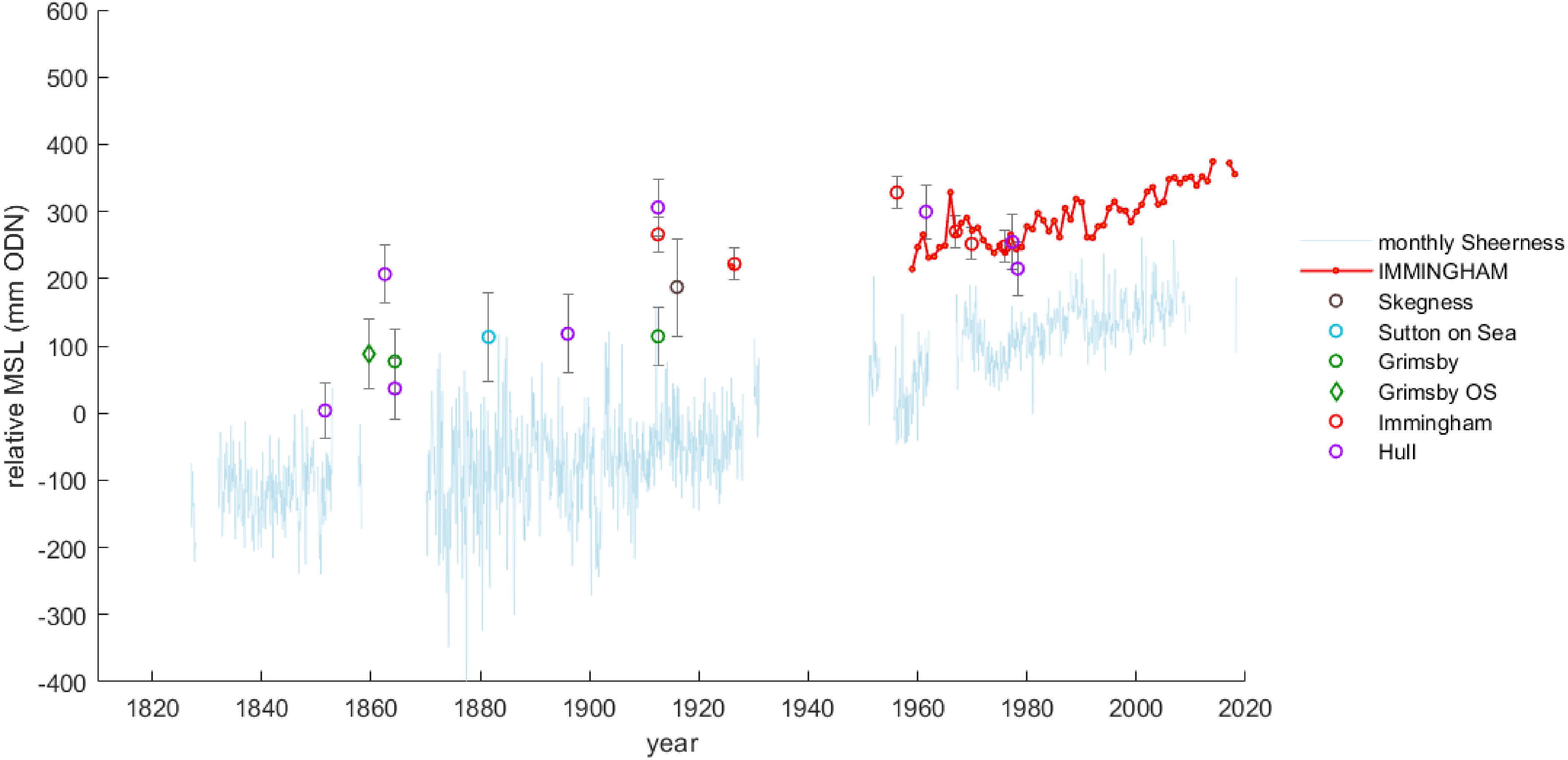
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
FELIXSTOWE
HARWICH
WALTON ON THE NAZE
Walton
Harwich
Harwich OS
Felixstowe

Lowestoft



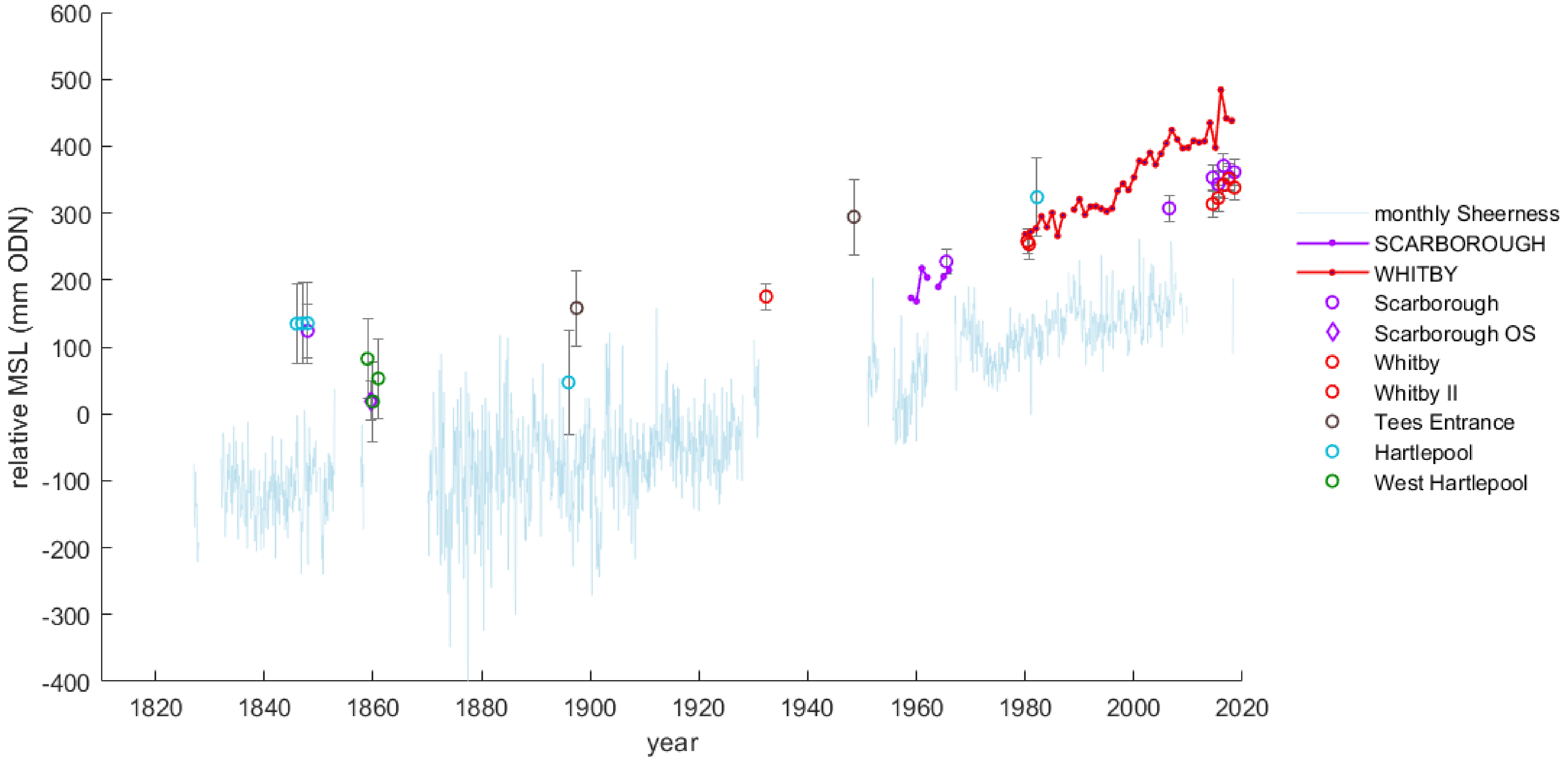
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
LOWESTOFT
CROMER
Lowestoft
Lowestoft OS
Gorleston
G Yarmouth
Caister
Cromer

Immingham



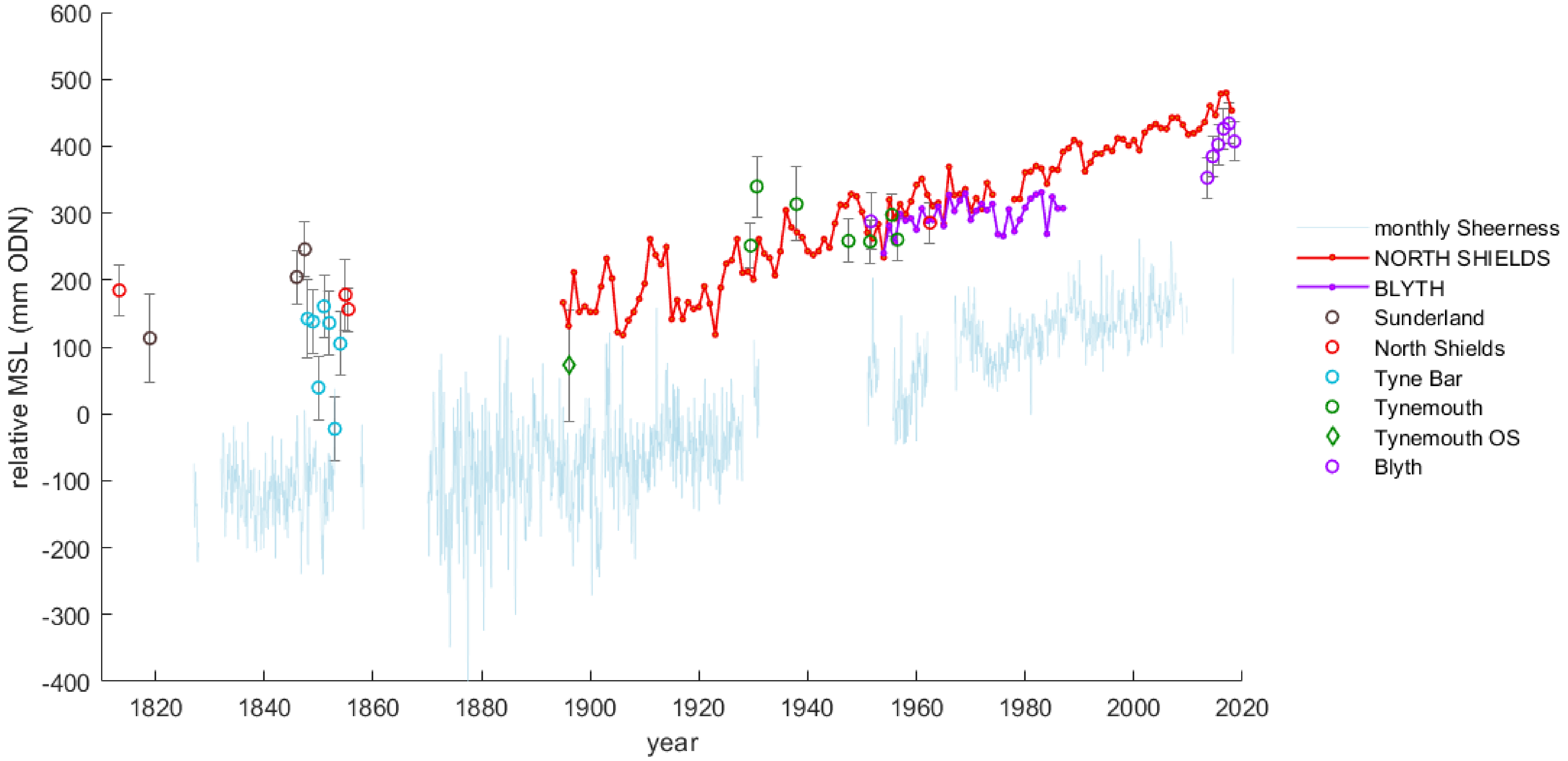
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
IMMINGHAM
Skegness
Sutton on Sea
Grimsby
Grimsby OS
Immingham
Hull

Whitby

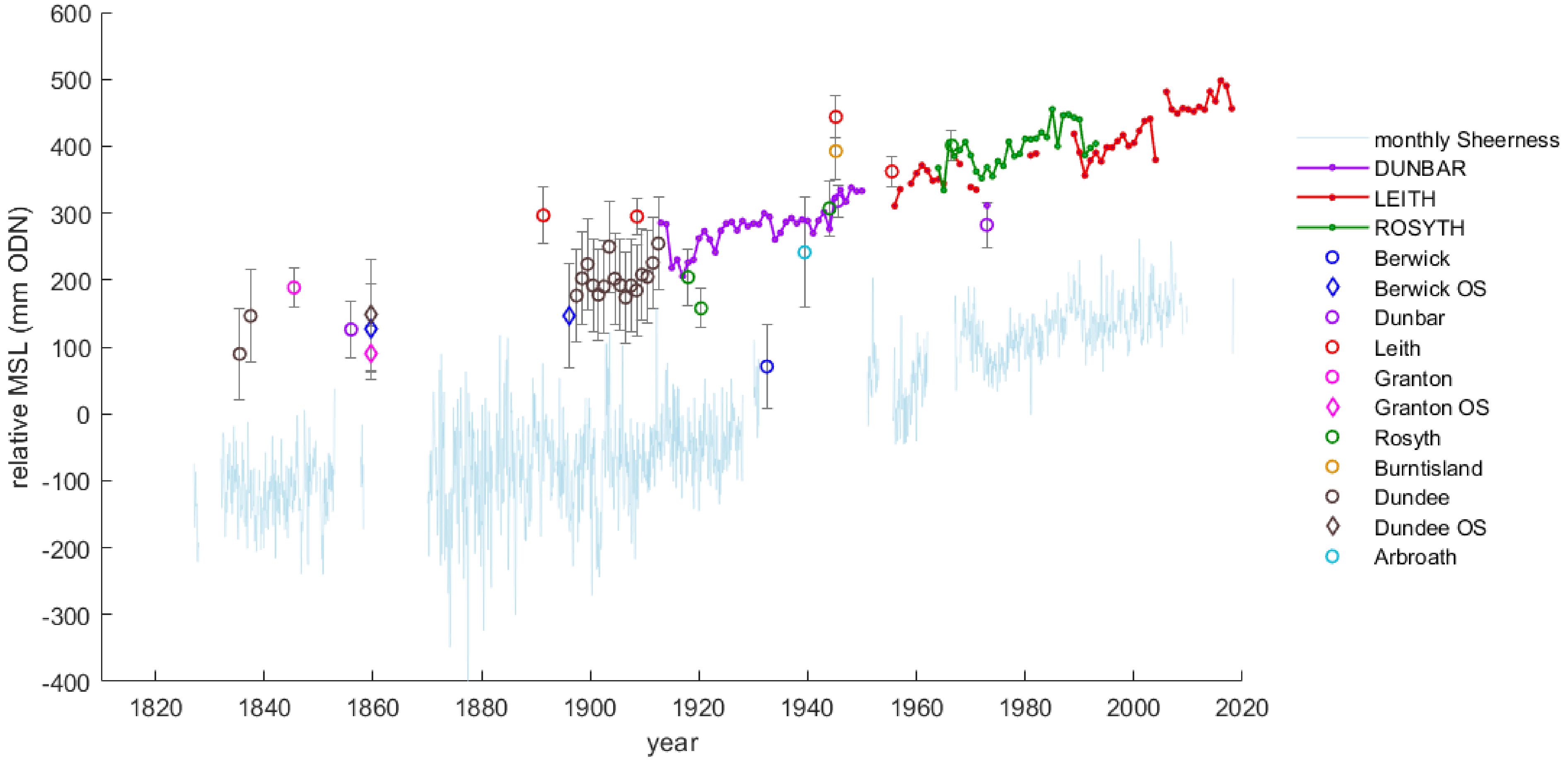


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
SCARBOROUGH
WHITBY
Scarborough
Scarborough OS
Whitby
Whitby II
Tees Entrance
Hartlepool
West Hartlepool

North Shields

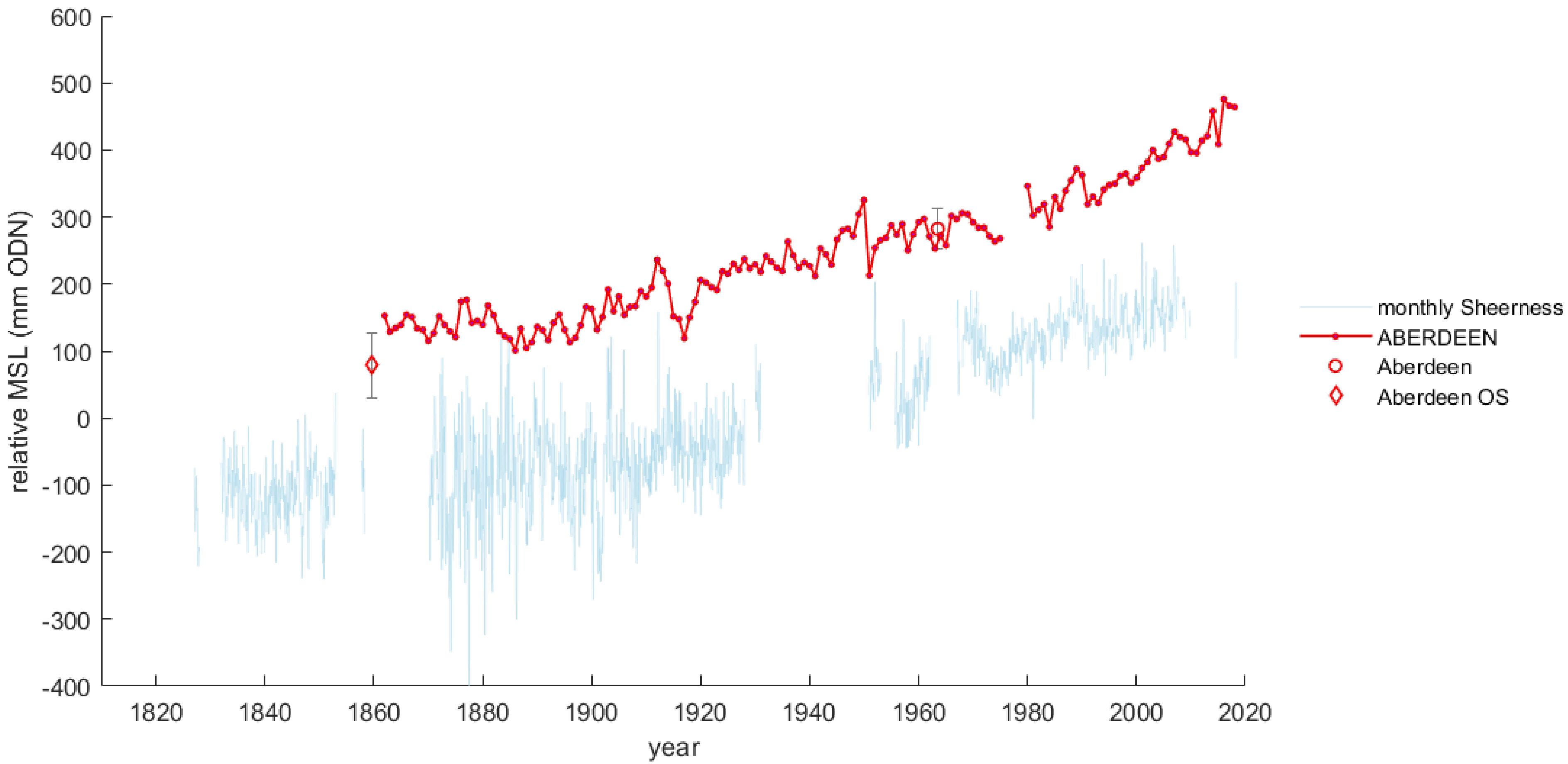


Leith



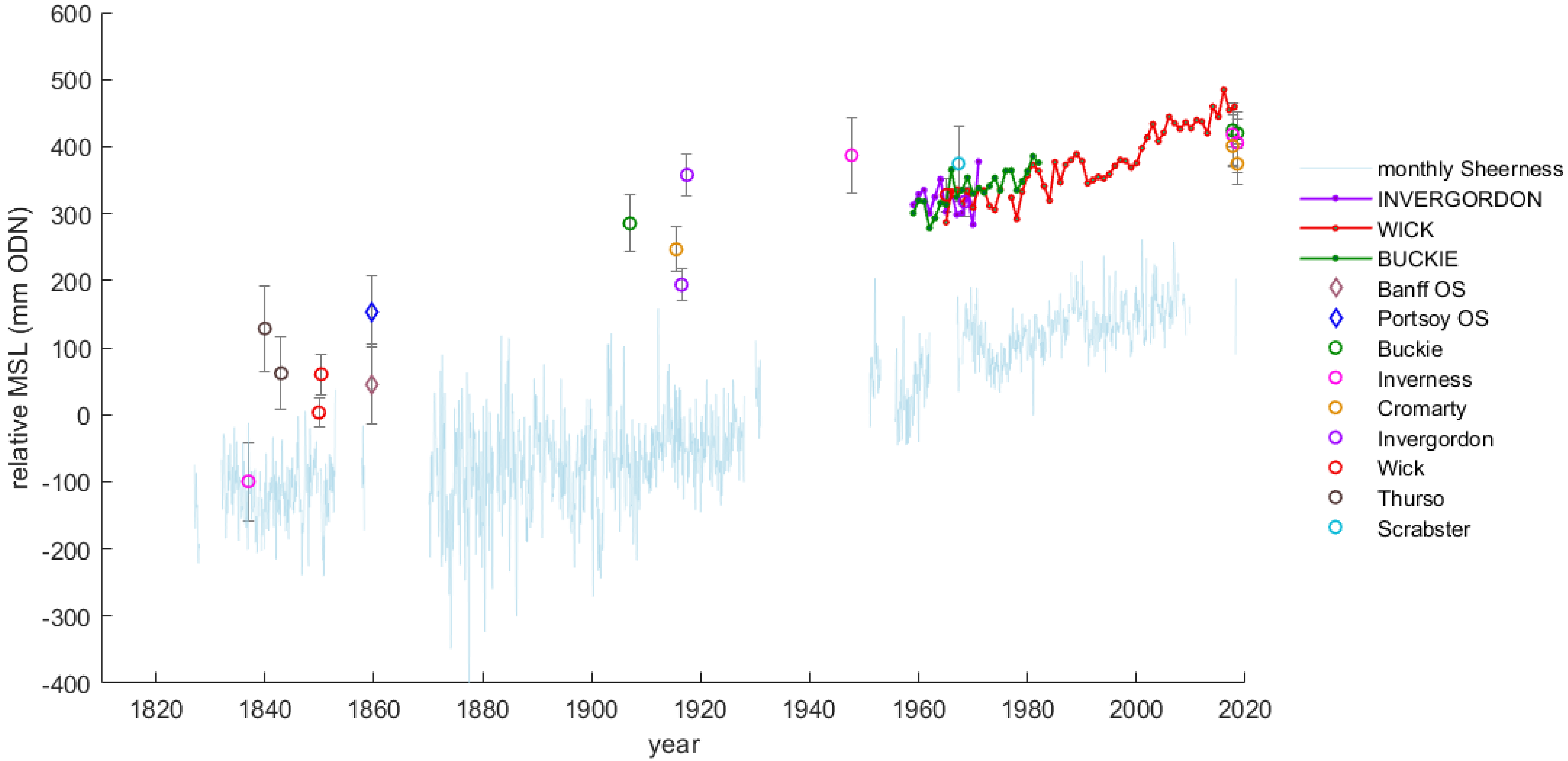
relative MSL (mm ODN)
600
500
400
300
200
100
0
-100
-200
-300
-400
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
DUNBAR
LEITH
ROSYTH
Berwick
Berwick OS
Dunbar
Leith
Granton
Granton OS
Rosyth
Burntisland
Dundee
Dundee OS
Arbroath

Aberdeen



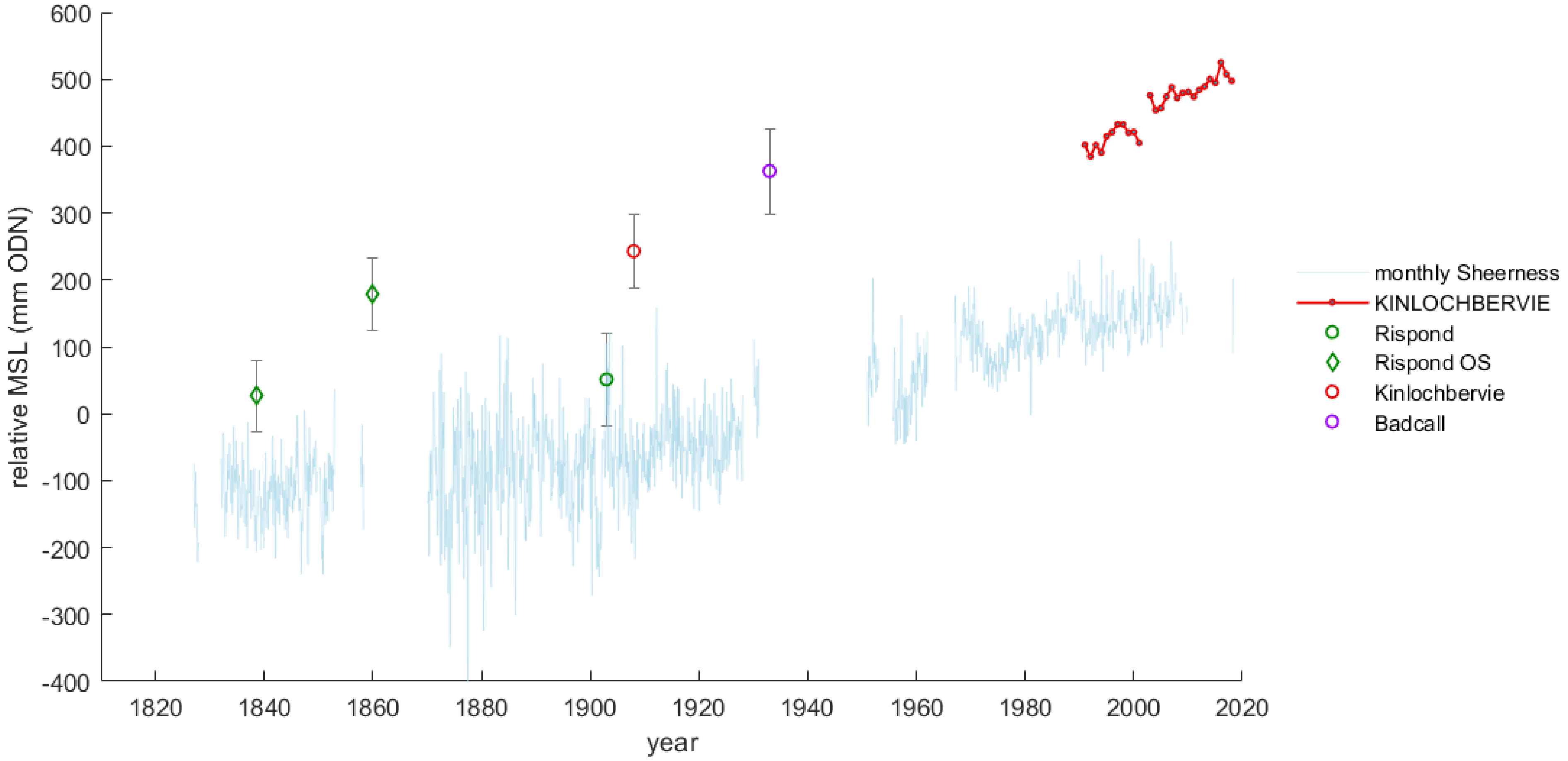
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
ABERDEEN
Aberdeen
Aberdeen OS

Wick

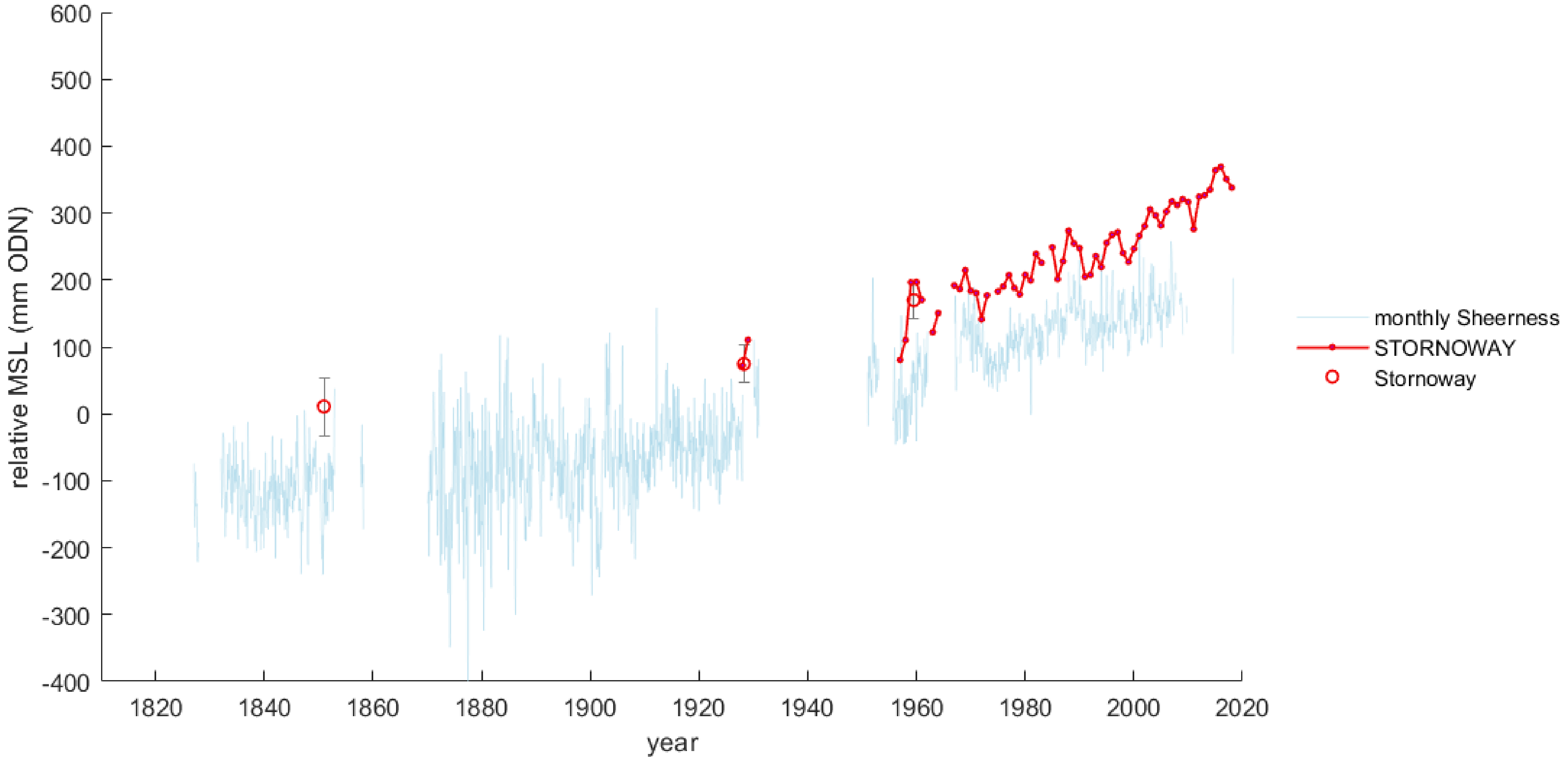


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
INVERGORDON
WICK
BUCKIE
Banff OS
Portsoy OS
Buckie
Inverness
Cromarty
Invergordon
Wick
Thurso
Scrabster

Kinlochbervie

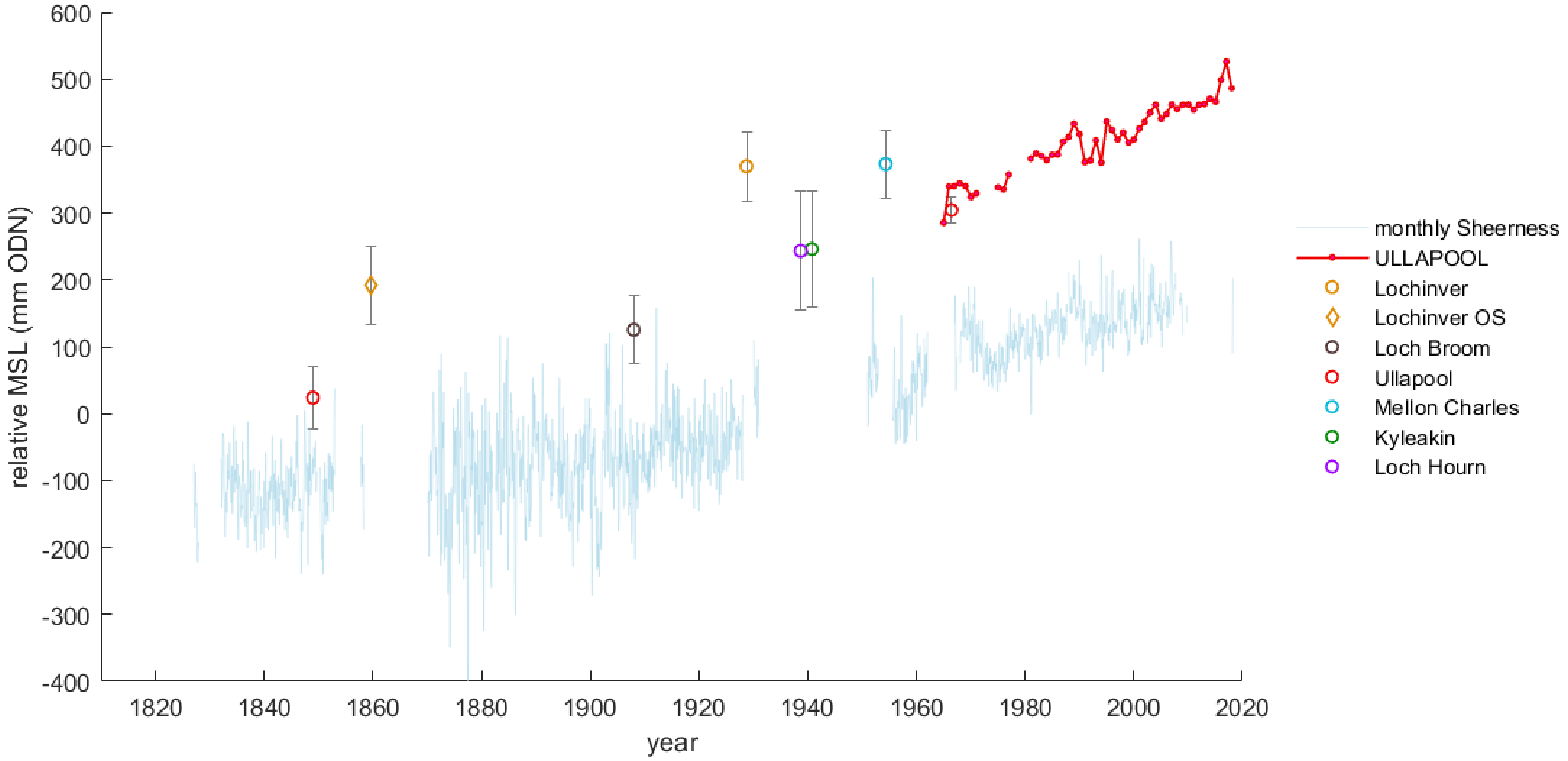


Stornoway



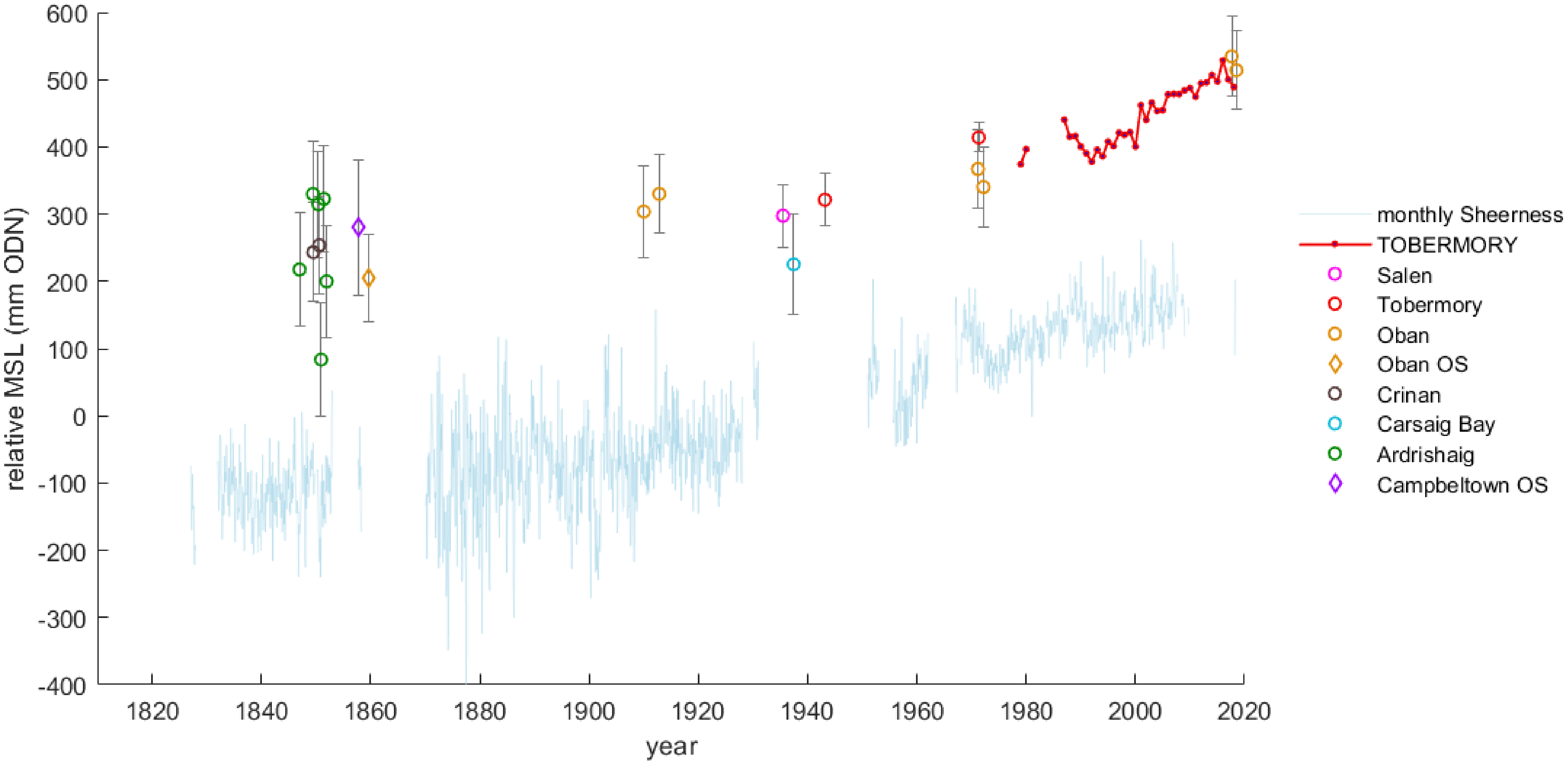
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
STORNOWAY
Stornoway

Ullapool



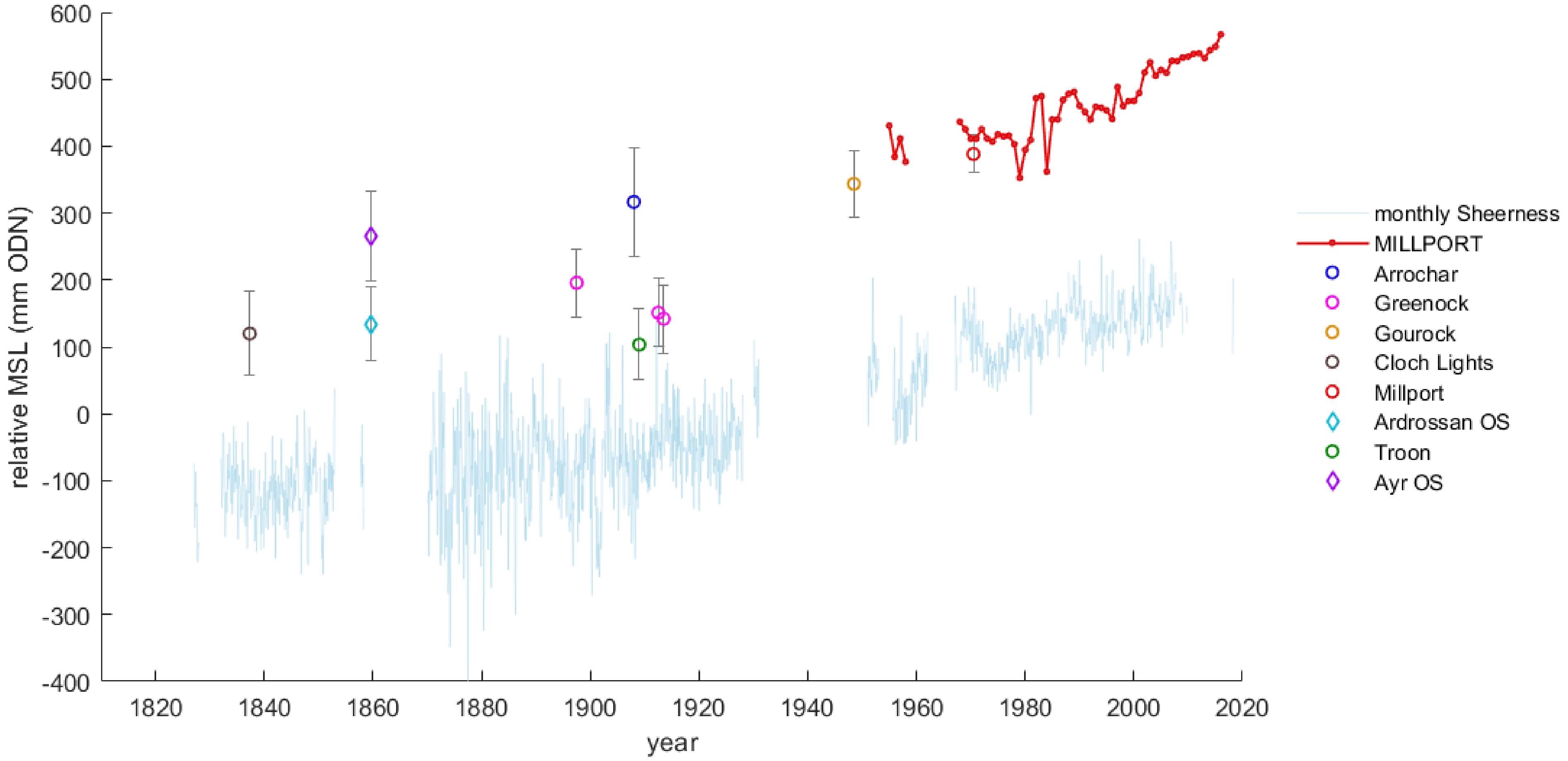
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
ULLAPOOL
Lochinver
Lochinver OS
Loch Broom
Ullapool
Mellon Charles
Kyleakin
Loch Hourn

Tobermory



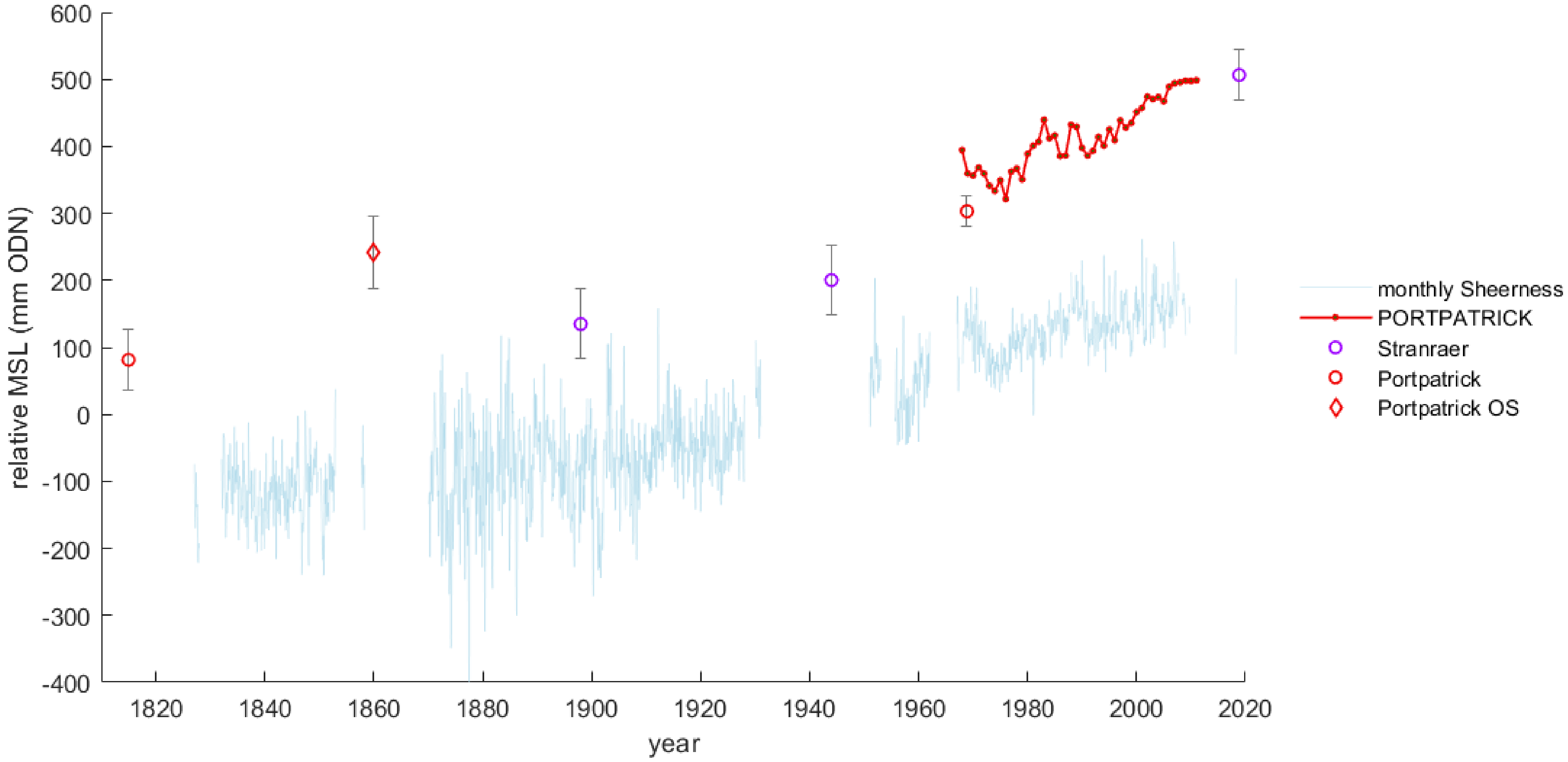
relative MSL (mm ODN)
600
500
400
300
200
100
0
-100
-200
-300
-400
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
TOBERMORY
Salen
Tobermory
Oban
Oban OS
Crinan
Carsaig Bay
Ardrishaig
Campbeltown OS

Millport

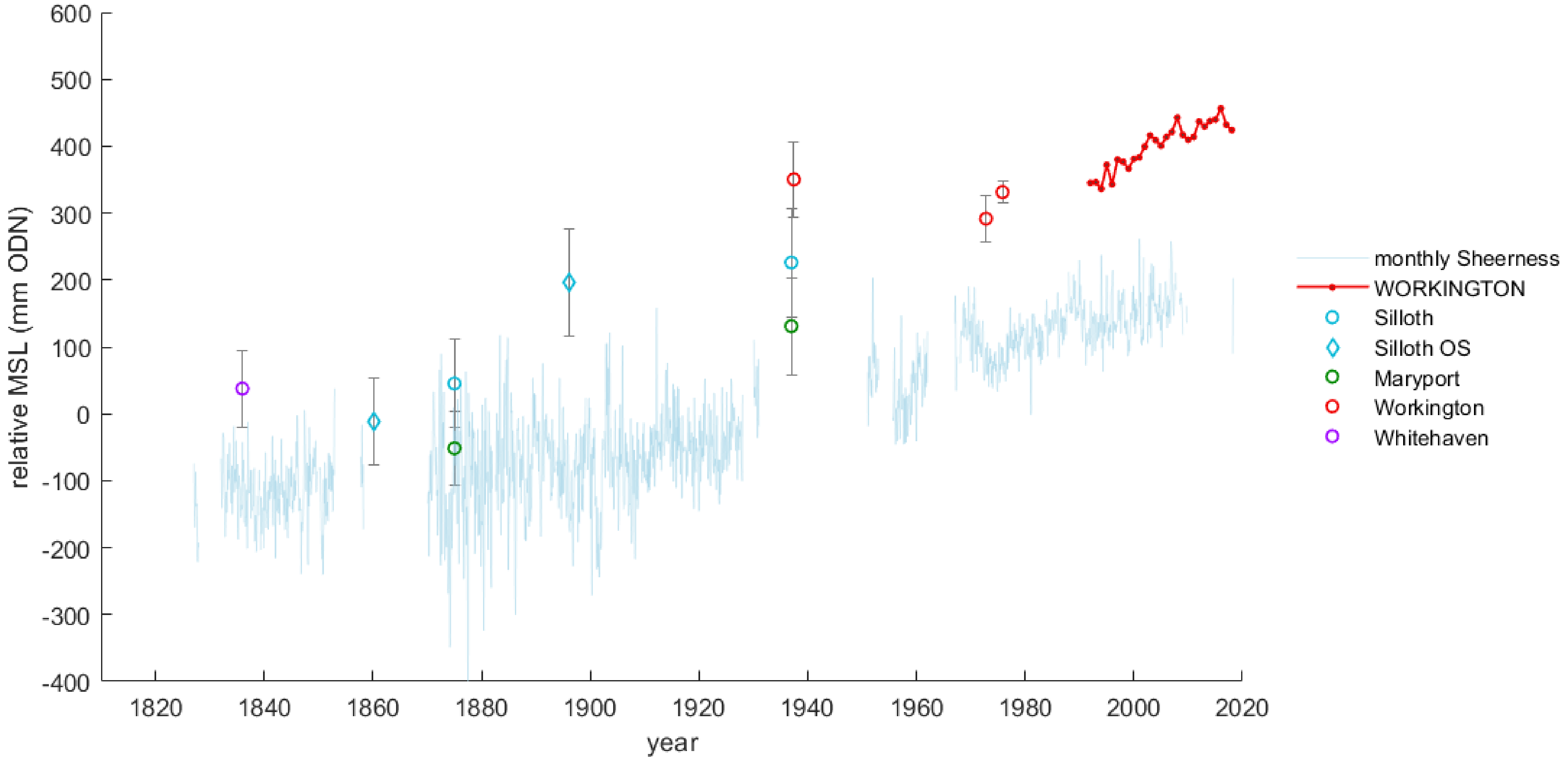


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
MILLPORT
Arrochar
Greenock
Gourock
Cloch Lights
Millport
Ardrossan OS
Troon
Ayr OS

Portpatrick

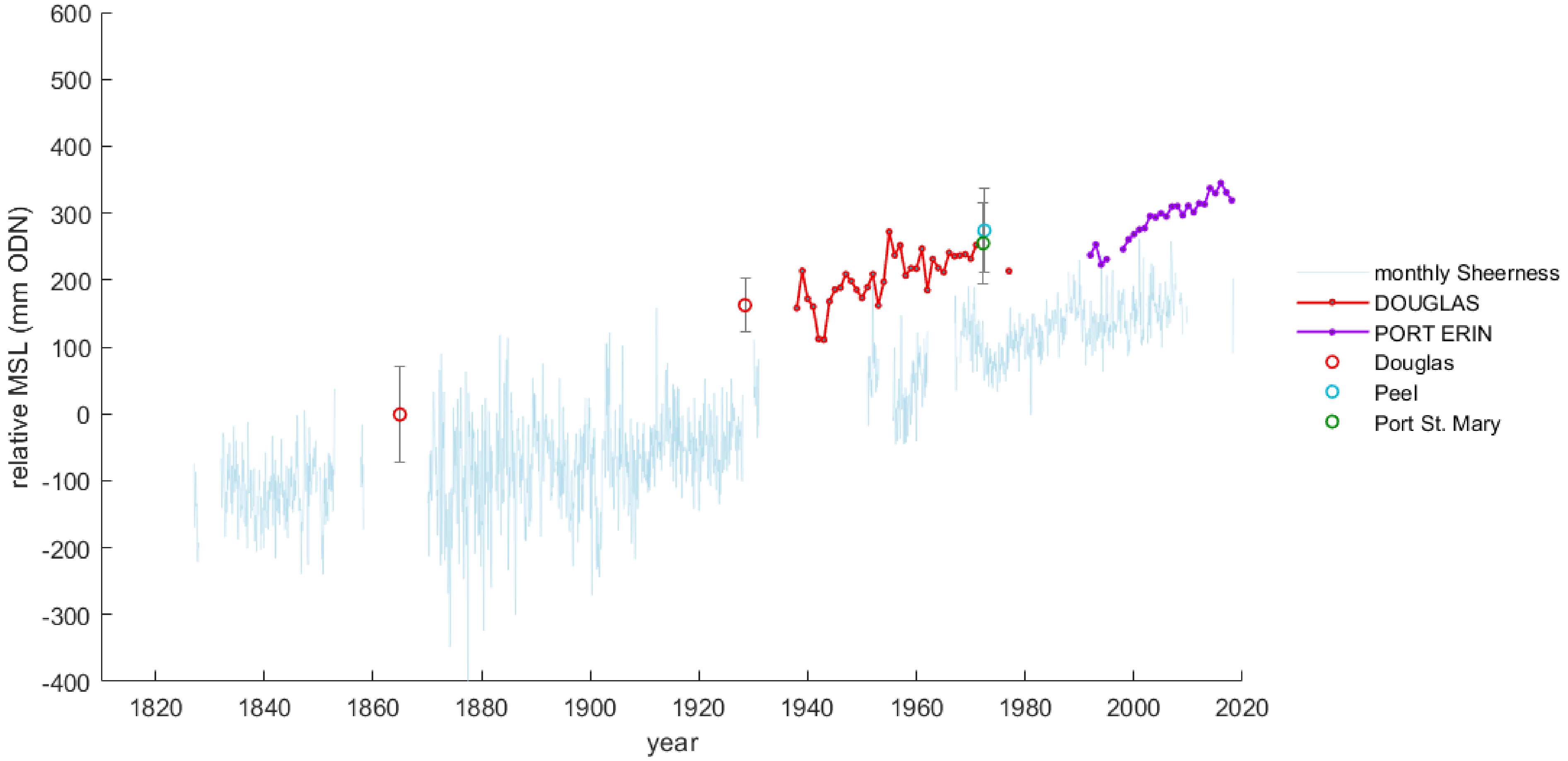


Workington



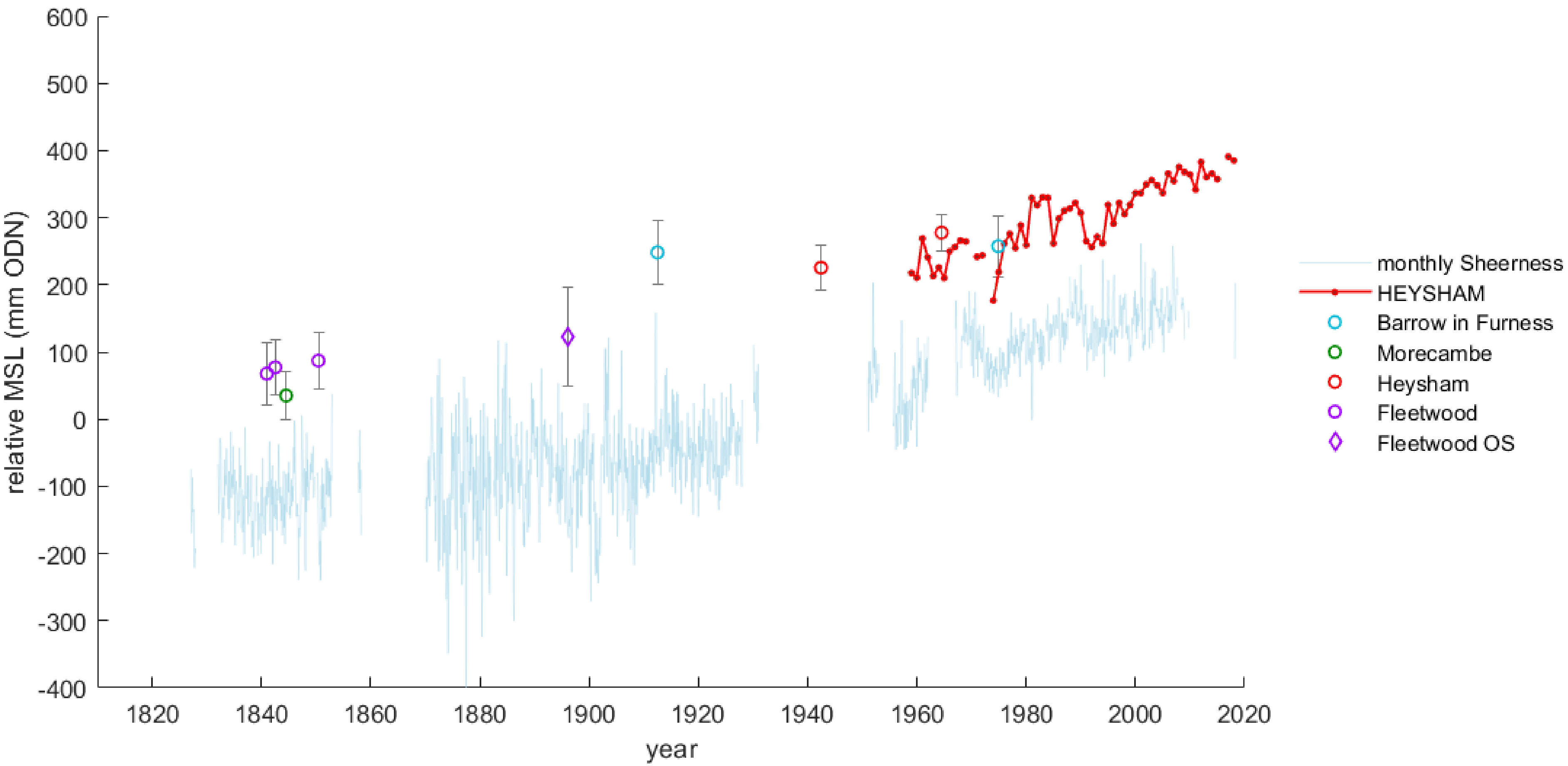
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
WORKINGTON
Silloth
Silloth OS
Maryport
Workington
Whitehaven

Douglas

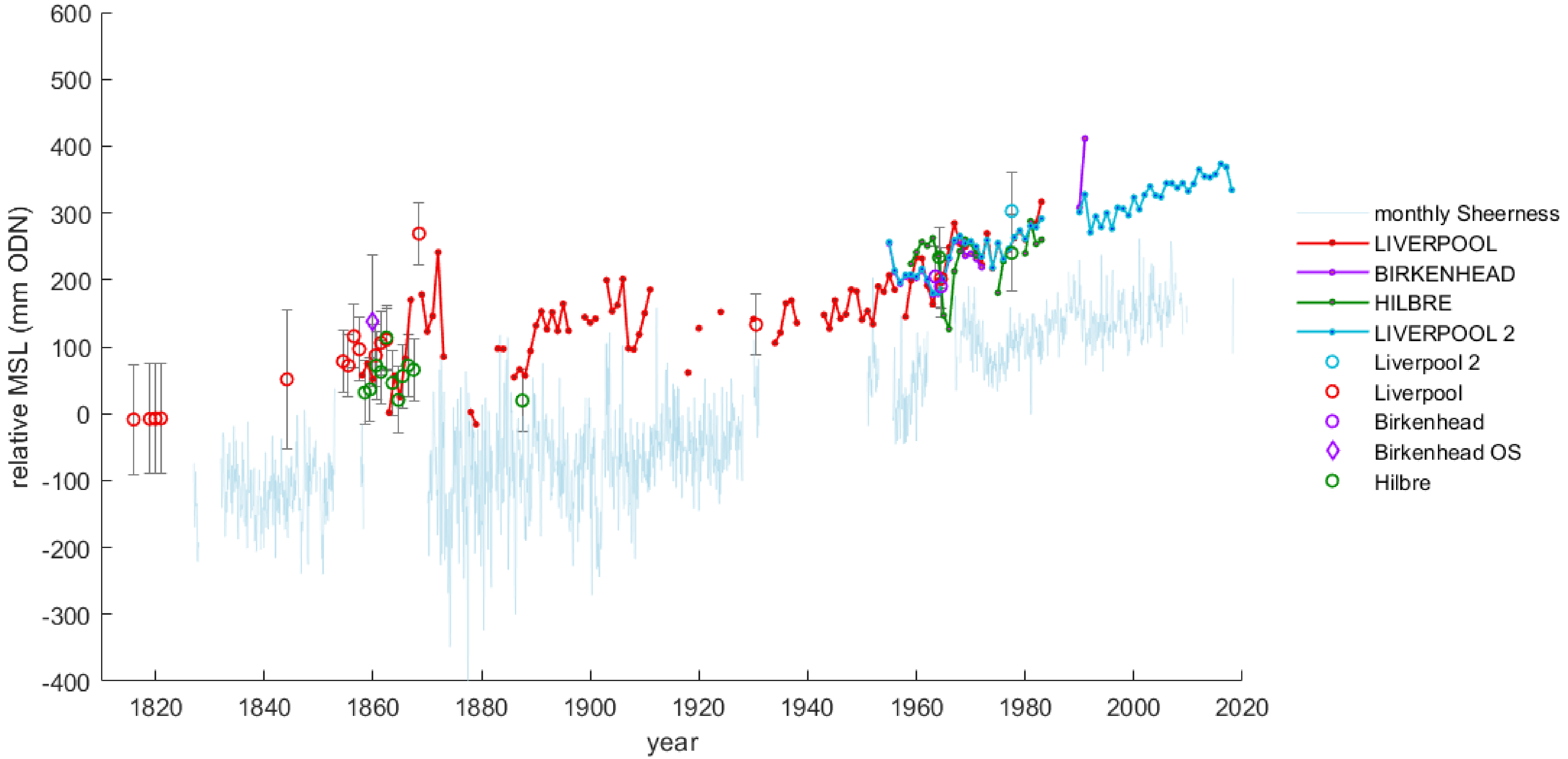


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
DOUGLAS
PORT ERIN
Douglas
Peel
Port St. Mary

Heysham

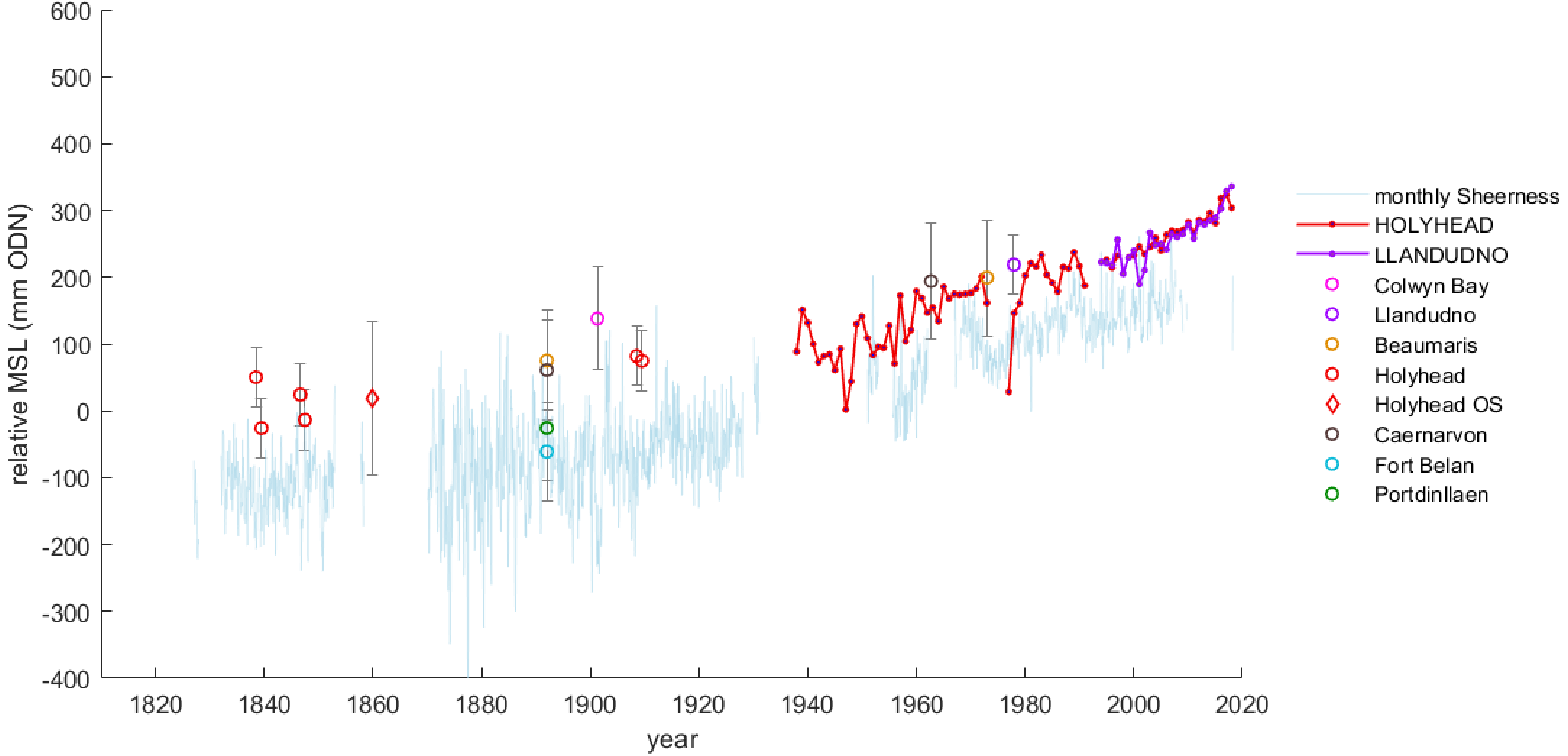

600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
HEYSHAM
Barrow in Furness
Morecambe
Heysham
Fleetwood
Fleetwood OS

Liverpool



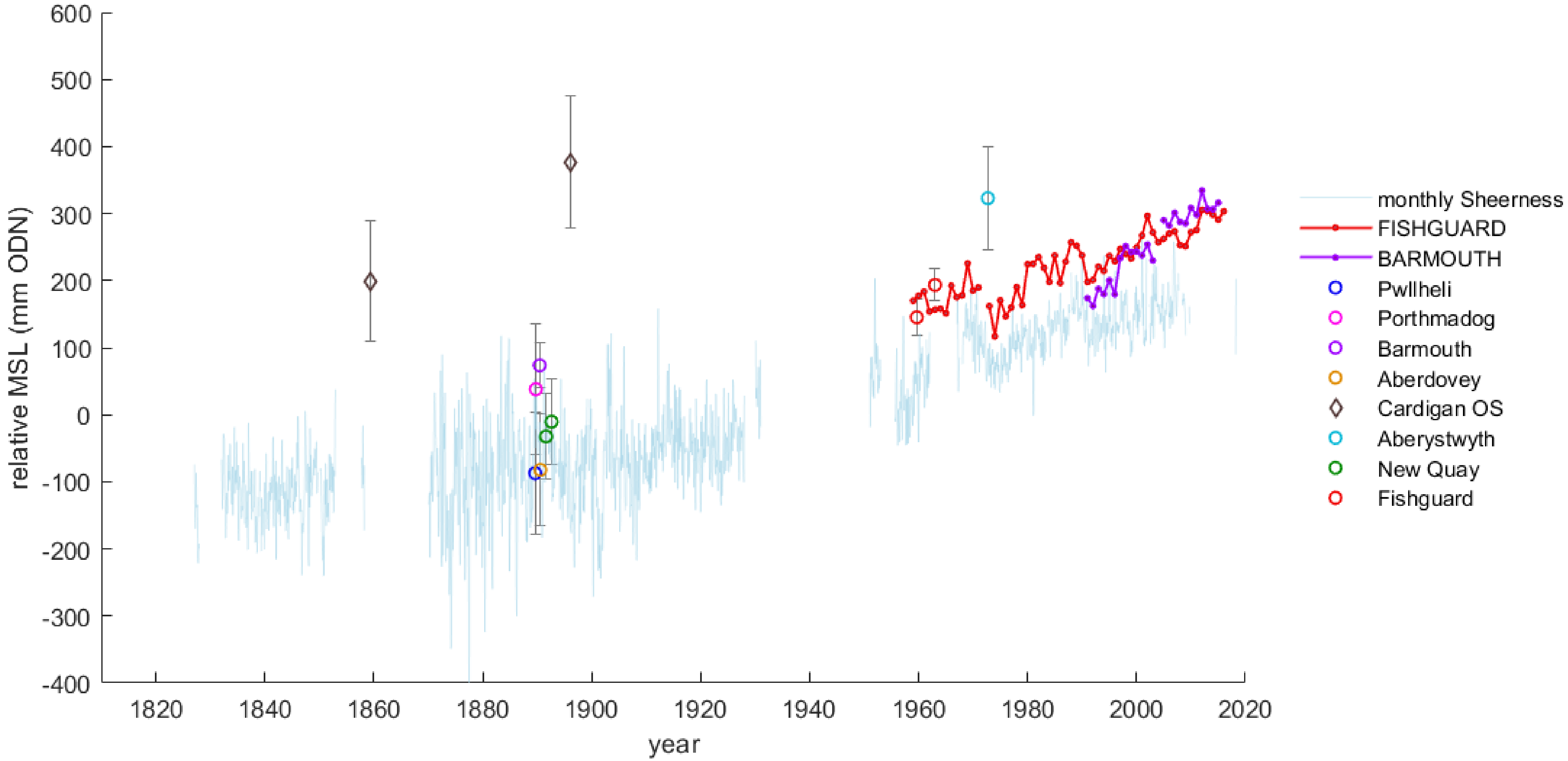
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
LIVERPOOL
BIRKENHEAD
HILBRE
LIVERPOOL 2
Liverpool 2
Liverpool
Birkenhead
Birkenhead OS
Hilbre

Holyhead



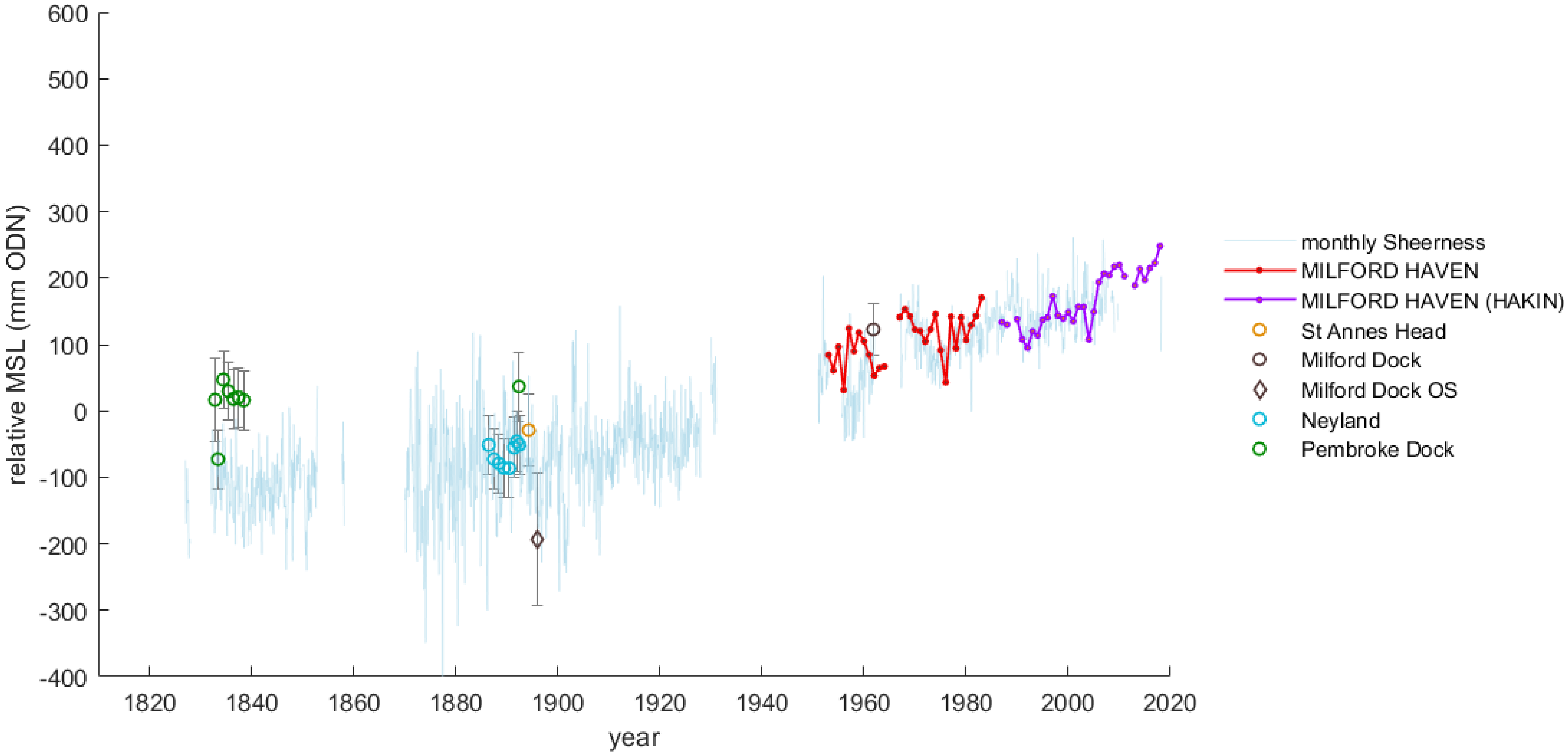
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
HOLYHEAD
LLANDUDNO
Colwyn Bay
Llandudno
Beaumaris
Holyhead
Holyhead OS
Caernarvon
Fort Belan
Portdinllaen

Fishguard

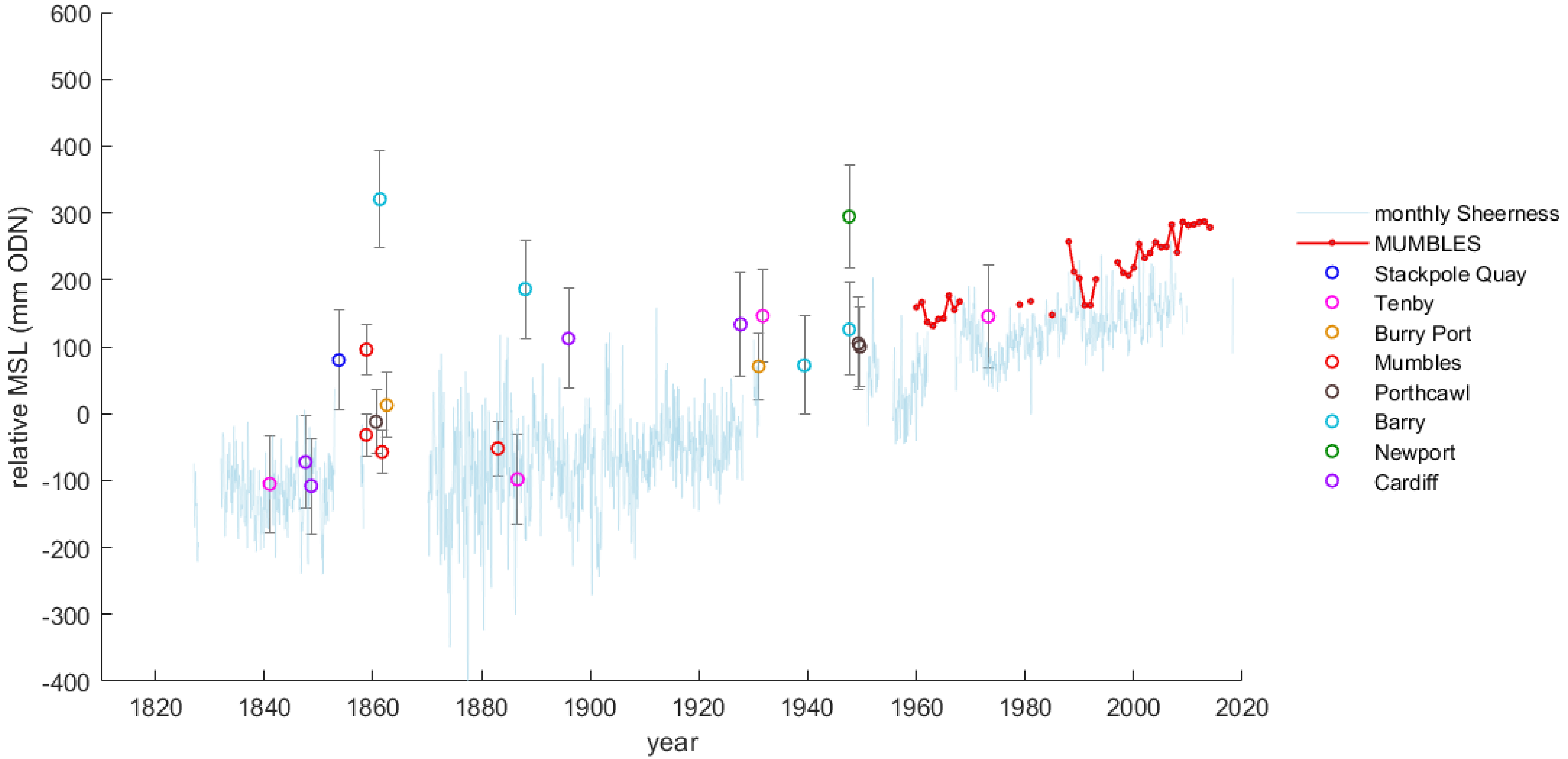


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
FISHGUARD
BARMOUTH
Pwllheli
Porthmadog
Barmouth
Aberdovey
Cardigan OS
Aberystwyth
New Quay
Fishguard

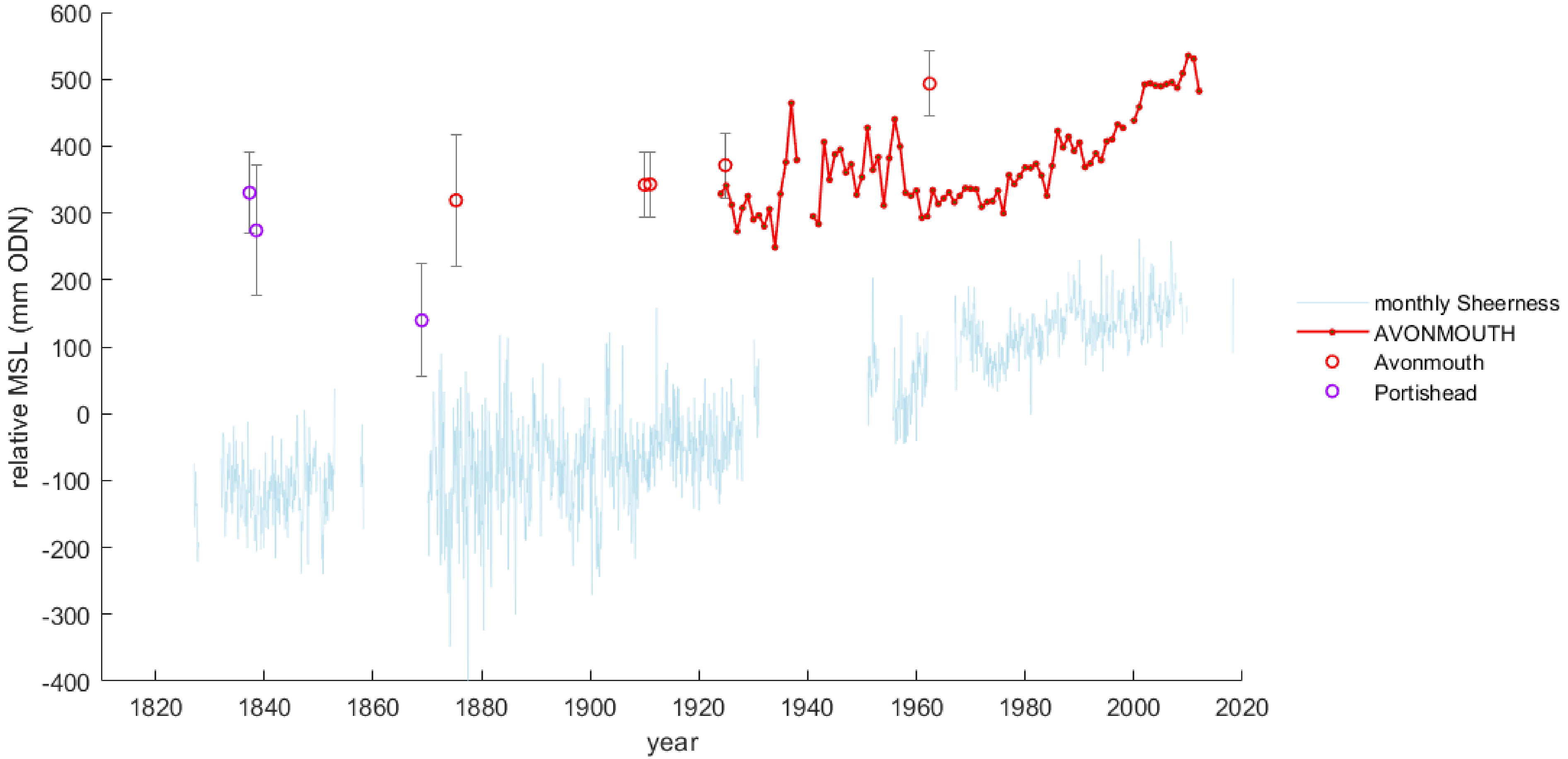
Milford Haven



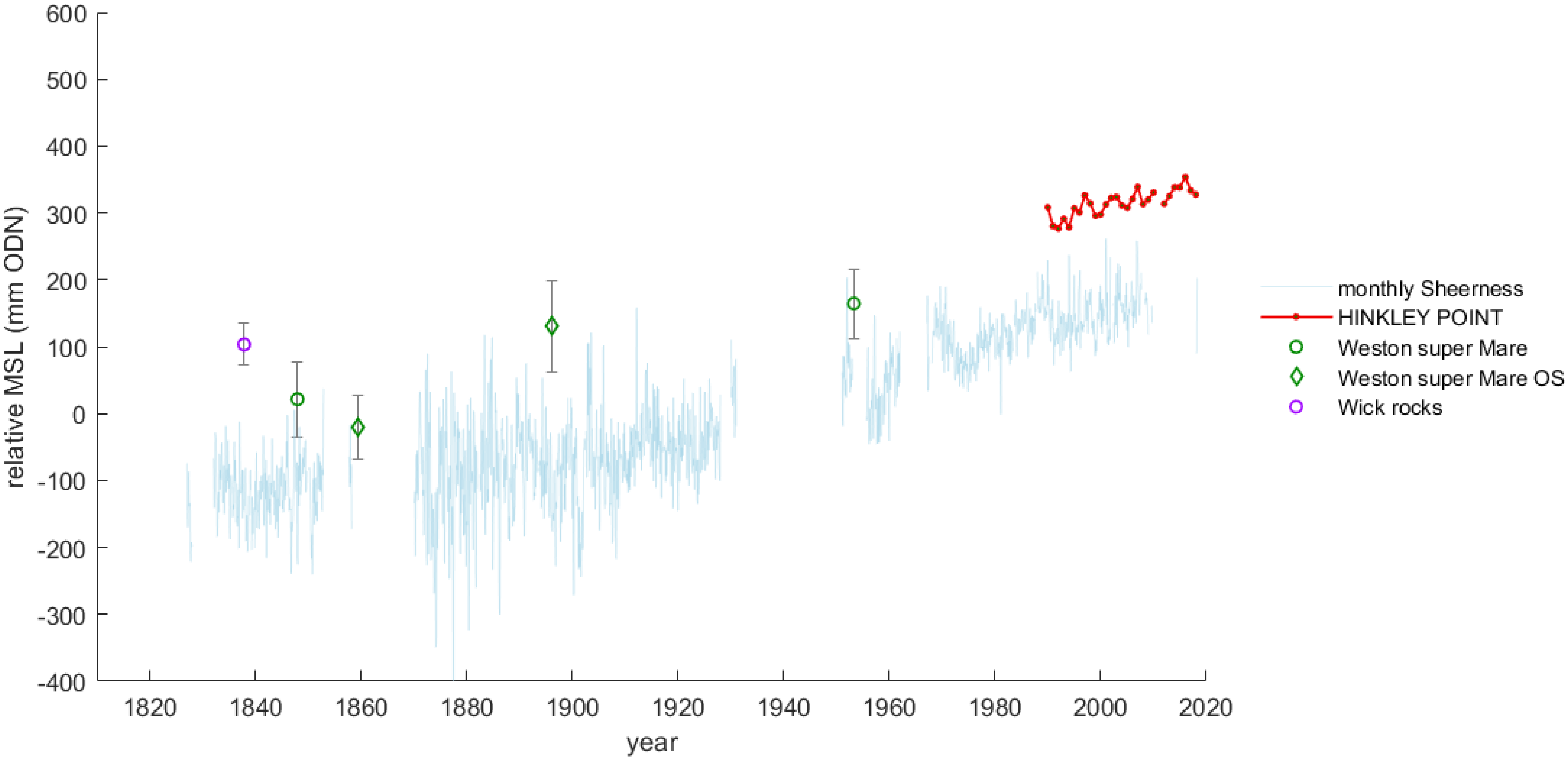
Mumbles


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
MUMBLES
Stackpole Quay
Tenby
Burry Port
Mumbles
Porthcawl
Barry
Newport
Cardiff

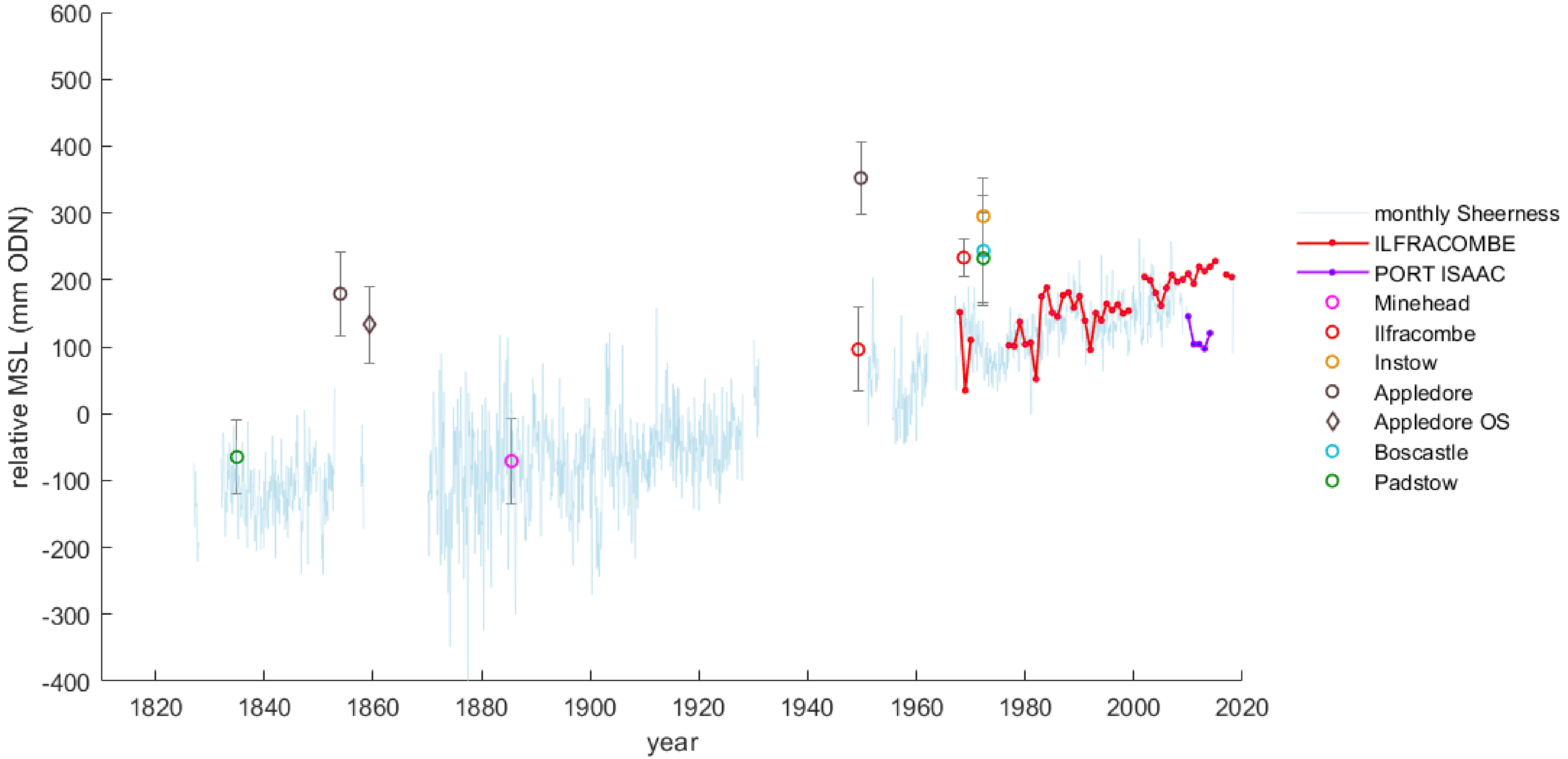
Avonmouth


600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
AVONMOUTH
Avonmouth
Portishead

Hinkley Point

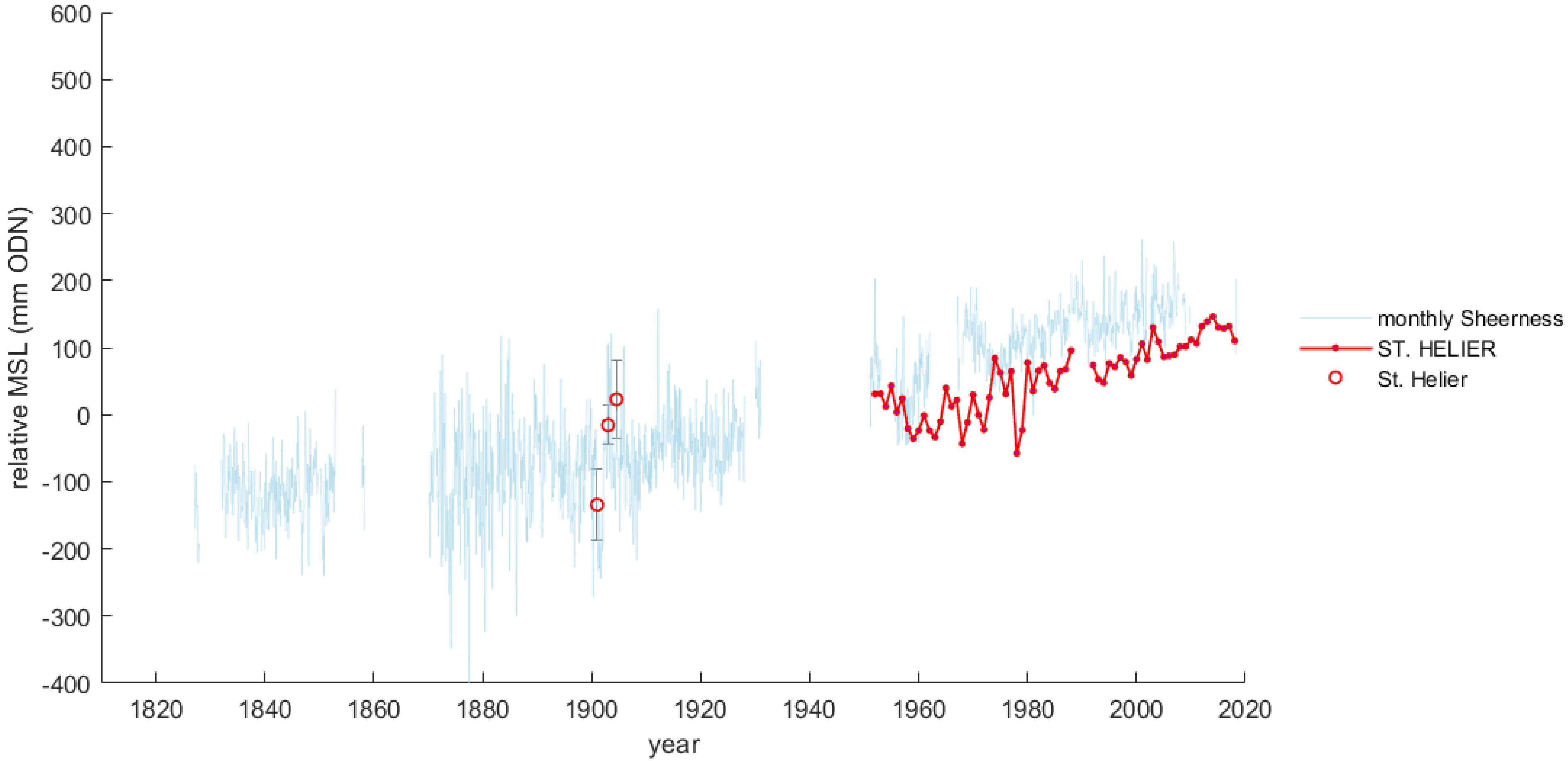


Ilfracombe



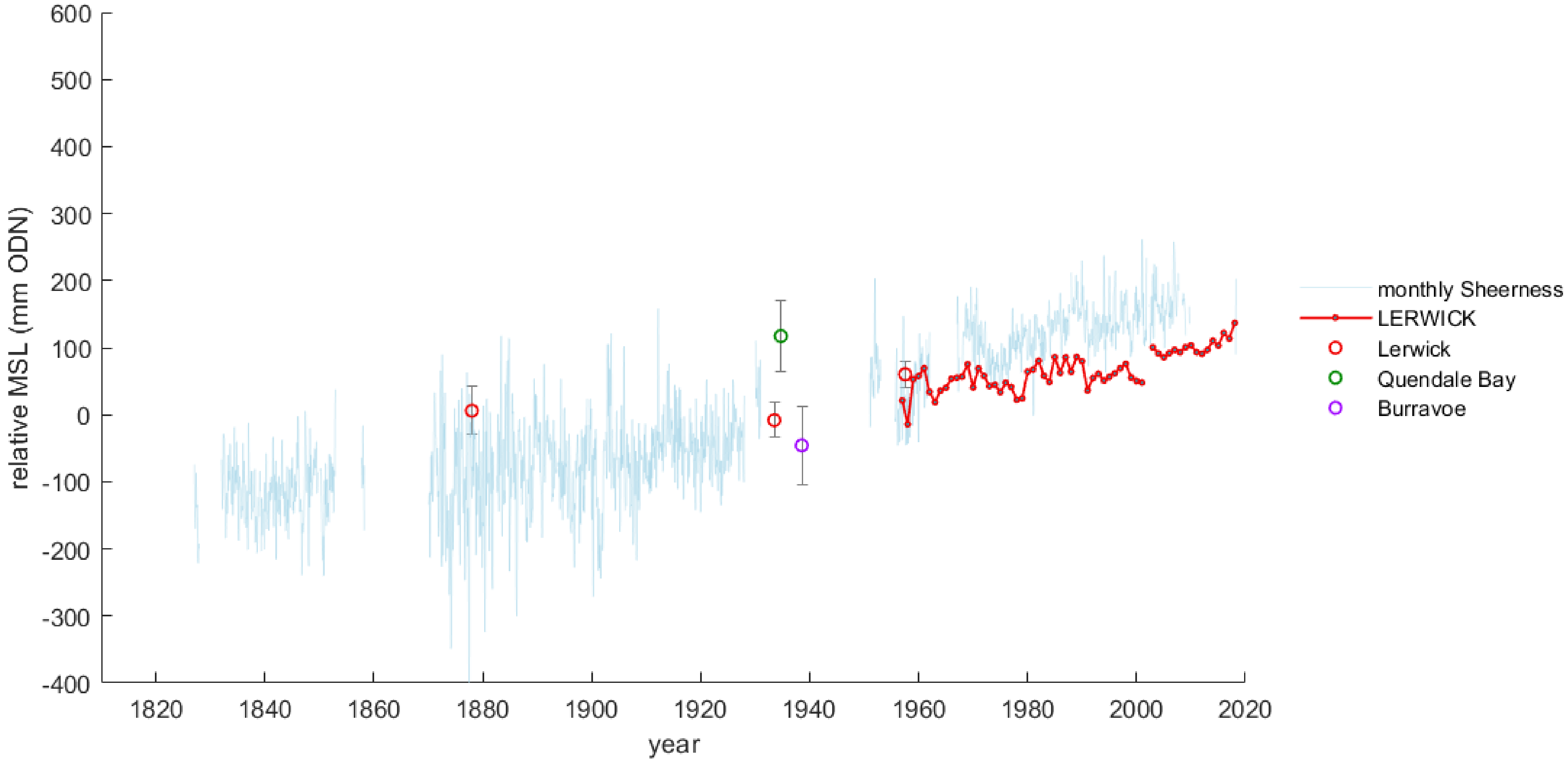
600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
ILFRACOMBE
PORT ISAAC
Minehead
Ilfracombe
Instow
Appledore
Appledore OS
Boscastle
Padstow

St. Helier



600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
ST. HELIER
St. Helier

Lerwick



600
500
400
300
200
100
0
-100
-200
-300
-400
relative MSL (mm ODN)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
year
monthly Sheerness
LERWICK
Lerwick
Quendale Bay
Burravoe

Plot of all data points from all sites superimposed adjusted to a common datum by subtracting the ODN offset derived for the 1958 to 2018 monthly MSL data